Final Authors' response for the manuscript titled "Risks of seasonal extreme rainfall events in Bangladesh under 1.5 and 2.0 degrees' warmer worlds – How anthropogenic aerosols change the story" by Ruksana H. Rimi et al., 2019.

We would like to thank the Editor and all Reviewers for their constructive comments and suggestions.

In this document, we sequentially present the replies to all reviewers (as added at the interactive discussion) and a marked-up version of the manuscript with author's edits in response to all comments.

Dear Editor,

We have attached the detailed replies to the reviewers' comments that are also available online in the open discussion. Afterwards, we have added a marked-up version of the manuscript with author's edits in response to all three reviewers.

In addition to the reply to the reviewers, we made some extra changes in the paper. For instance we have included in the revised manuscript

1. In the introduction we explain the context of HAPPI project development.
2. Additional four HAPPI model data analyses are added to compare with HadRM3P model results. Such comparison can test the robustness of results from HadRM3P model and significantly strengthen this paper by getting over the problem of model uncertainty.
3. In conclusion, a more emphasis is given on the fact that for the first time, a multi-model assessment of both present and future risks of extreme rainfall events considering anthropogenic climate change drivers of GHGs and aerosols is done at sub-regional local scale in Bangladesh in this paper.
4. Information about prescribed fields of SO_2 emission in the HadRM3P model is added because of the importance of the role played by the aerosols. But for the sake of better readability of this paper, this information is added in the supplementary material.

We hope that the current version of the manuscript contains sufficient amendments to address the comments made by the reviewers. We hope that this manuscript version will get a positive decision.

Best regards,
Ruksana Rimi

Response to Reviewer 1

We thank for the constructive comments from the anonymous Reviewer 1. We have carefully revised the manuscript to incorporate necessary amendments as per suggestions. Responses to the Referee Comments 1(RC1) are presented in the following paragraph in the Author's Comments 1(AC1):

Introduction

RC1: *The introduction provides a general background on the research topic with clearly stated objectives and research question. The author divided whole Bangladesh into four sub-regions (page 3, line11-14) to evaluate the risk of extreme rainfall events. Are there other specific reasons for to divide into four seasons like climatological variation or any other previous study used these sub-regions.*

AC1: These 4 sub-regions of Bangladesh and the different seasons are used for a reason. The three wet seasons with substantial climatological variations include: pre-monsoon (during Mar-Apr-May; MAM), monsoon (during Jun-Jul-Aug-Sep; JJA) and post-monsoon (Oct-Nov; SON). Little or no rain occurs in winter (during Dec-Jan-Feb; DJF). This dry winter season is excluded from our analysis because we are interested in wet extremes. Any MAM extreme rainfall events are known to cause flash floods and substantial crop damage (Ahmed et al., 2017).

Bangladesh receives more than 75% of the annual total rainfall during JJAS (Shahid, 2010). An extreme rainfall event in this period can therefore cause wide-spread flooding and landslide eventually leading to loss of lives and livelihoods. A high impact SON rainfall event may be associated with the coastal floods that occur due to storm surges or tidal effects along the northern part of Bay of Bengal (Hossain, 1998).

Considering both meteorological hazards and potential impacts, we have looked at extreme rainfall events of pre-monsoon and monsoon seasons and excluded the post-monsoon season. The same 4 sub-regions are used in Rimi et al., (2019) where, we evaluate the model's performance in simulating extreme events (see Fig. AC1.a). We believe that the pre-evaluated model simulations over the same 4 sub-regions provide confidence in analyzing the extreme rainfall events under different forcing scenarios.

In the revised manuscript, we have added the following lines at **page 5 lines 16-24**: "In Bangladesh, any MAM extreme rainfall events are known to cause flash floods and substantial crop damage (Ahmed et al., 2017). Bangladesh receives more than 75% of the annual total rainfall during JJAS (Shahid, 2010). An extreme rainfall event in this period can therefore cause wide-spread flooding and landslide eventually leading to loss of lives and livelihoods. A high impact post-monsoon (Oct-Nov; ON) rainfall event may be associated with the coastal floods that occur due to storm surges or tidal effects along the northern part of Bay of Bengal (Hossain, 1998). Considering meteorological hazards and potential impacts, MAM and JJAS extreme rainfall events are analyzed in this study while, ON rainfall events are excluded. Winter (during Dec-Jan-Feb; DJF) season is also excluded because little or no rain occurs during DJF and we are interested in wet extremes."

And added the following lines at **page 5 lines 28-30**: "The model's performance in simulating extreme rainfall events over these same 4 sub-regions is evaluated in Rimi et al., (2019). Such pre-evaluated model simulations provide confidence in analyzing comparative risks of extreme rainfall events under different forcing scenarios."

RC1: A standalone Figure of Bangladesh including the four sub-regions could be useful with mean seasonal rainfall.

AC1: Because a standalone figure of Bangladesh including the four sub-regions with mean seasonal rainfall has already been shown in Rimi et al., 2019 (see Fig AC1.b); we are not using the same kind of figure in this paper. Nevertheless, the sub-regions are indicated in panel e of Fig 2 & 3 of this manuscript.

RC1: Line 16 page 2 – In June 2017, heavy rainfall killed at least 156 people (needs a citation).

AC1: The following citation is added for this information in the revised bibliography at **page 15 lines 13-15**: Paul, R. and Hussain, Z.: Landslide, floods kill 156 in Bangladesh, India; toll could rise, Reuters, 14th June [online] Available from: https://uk.reuters.com/article/uk-bangladesh-landslides/landslide-floods-kill-156-in-bangladesh-india-toll-could-rise-idUKKBN1950AG, 2017.

Data and Methods

Model setup and experiment design

RC1: The wettest and driest years are not well presented in the Table S2. Is it range of years or individual year? Classification of wet years and dry is not clearly mentioned. It has been mentioned that spatiotemporal average of rainfall has been used here. Is there any threshold for the classification of wet period and dry period? In Bangladesh flooding years are considered as wet year during monsoon. This needs to be made clear.

AC1: We identified the two wettest and two driest years during 2006–2015 over each of the four sub-regions of Bangladesh using ACT data. This identification process involved comparing the magnitude along with return periods of rainfall events during MAM and JJAS in each of the years throughout 2006 to 2015 (ACT model ensemble with 200 members per year used). Then a pair of wettest and driest years is used to approximately indicate the noise-to-signal ratio.

For example, according to ACT model ensemble, during monsoon season at sub-region 2, the wettest years with extreme rainfall events are 2008 and 2012 (see Fig. AC1.c, the red and blue dots for individual model runs and shadings for 5-95% confidence intervals) and the driest years are 2006 and 2013 (yellow and cyan dots for individual model runs and shadings for 5-95% confidence intervals). Using the pair of these wettest and driest years from the model ensemble, we could demonstrate the plausible spread of the rainfall events within this model ensemble as a measure of noise-to-signal ratio.

Because this model ensemble has same forcings in each year for the historical period of 2006-2015, the only variability playing a role in changing the intensity of rainfall is natural variability of sea surface temperatures (SSTs). The use of two wettest and driest years, therefore explains how much natural variability of SSTs contributes to the variability of rainfall intensities over this study area.

We agree with your comment and changed the presentation of the years in the supplementary Table 2 to make it clear that they are the two individual years with either wettest or, driest conditions in a 10-year period over a specific sub-region.

In the revised manuscript, we have added the following lines at **page 6 lines 20-23**: "ACT model ensemble has the same forcings in each year for the historical period of 2006-2015; the only variability playing a role in changing rainfall intensity is therefore the natural variability of SSTs. For this reason, these two wettest and driest years of ACT model ensemble approximately indicate how much natural SST variation can contribute to changing rainfall intensities."

Results and Discussion

Section 3.1 Model Evaluation for Five day mean rainfall

RC1: "Five day mean rainfall is used to represent the timescale responsible for river flooding as opposed to daily extremes that cause flash floods primarily in the pre-monsoon season." Is the 5 days rainfall causes flooding or 1-day extreme rainfall causes flash flood in Bangladesh and what is the intensity of rainfall termed as extreme (what is the amount of rainfall mm/day considered as extreme value)? Citation may clear this statement.

AC1: By extreme rainfall event, we mean a high impact rainfall event (i.e., sufficient to cause flooding or landslides) with up to 100 year return period (a rare event with low frequency of occurrence). The intensity of the rainfall event can vary depending on both location and season.

For example, at north-east Bangladesh, in pre-monsoon season, more than 150 mm rainfall event over a 6-day period can lead to an early flash flood (Ahmed et al., 2017). On the other hand, at south-east parts of Bangladesh, in monsoon season, more than 350 mm rainfall events over a 3-day period is enough to cause a landslide (Ali et al., 2014). Whereas, for a wide-spread river flooding e.g., the Brahmaputra River Basin flooding in August 2017, 10-day extreme rainfall event is considered (Philip et al., 2018). Considering the range from 1- to 10-day high impact rainfall events that can trigger flooding and landslides in Bangladesh, we focused on daily and 5-day events because these events can provide a typical idea about the potential risks.

We have added the lines in the revised manuscript at **page 5 lines 32-40**: "In Bangladesh 1- to 10-day high impact rainfall events can trigger flooding and landslides. For example, at north-east Bangladesh (sub-region 2), more than 150 mm MAM rainfall over a 6-day period can lead to an early flash flood (Ahmed et al., 2017). In contrast, at south-east Bangladesh (sub-region 4), more than 350 mm JJAS rainfall over a 3-day period is enough to cause a landslide (Ali et al., 2014). For a wide-spread river flooding e.g., the Brahmaputra River Basin flooding in August 2017, 10-day extreme rainfall event is considered (Philip et al., 2018). Considering such variations in rainfall magnitudes causing different hazards, we focused on daily and 5-day rainfall events to analyze the potential risks.
The seasonal cycles of presented here are based on 5-day rainfall, which is used to represent the timescale responsible for river flooding as opposed to daily extremes that cause flash floods primarily in the pre-monsoon season."

RC1: Fig.1 represents annual cycle of the four sub-regions in Bangladesh and results of the five models (ACT, NAT, GHG, HAPPI 1.5 and HAPPI 2.0) show maximum rainfall occurs in June. June to September is the monsoon month and June is the month of monsoon onset. Usually, July is the maximum rainfall month in Bangladesh. Do the results indicate any shifting of monsoon timing Due to the monsoon climate, the overall variation (inter-annual) of rainfall in JJAS months (seasonal) is not quite high? Bangladesh has almost similar pattern of monsoon precipitation in the JJAS months. Underestimation by 25-65% is quite high. The bias and uncertainty within these values is very high. The authors need to explain the reasoning for this a bit more.

AC1: No, as per observational data (APHRODITE and CPC) that are used in the annual cycles in Fig 1; there are no indications of temporal shifting of monsoon. We find an early monsoon onset in the model simulations. Such early onset of monsoon is also reported in other model based studies (e.g., in Caesar et al., 2015; Fahad et al., 2017; Janes and Bhaskaran, 2012).

At the time of writing this paper, APHRODITE was only available until 2007, so we used 1998-2007 data for comparison. Recently, APHRODITE has been updated until 2015, allowing us to use 2006-2015 data for comparison (CPC data is also used for 2006-2015 duration). As a result, APHRODITE and CPC observations are now in better agreement (see Fig. AC1.d) and model bias is also smaller than before (highest bias level of 65% dropped to 50%). The 25-50% underestimation of monsoon precipitation is quantified based on the model ensemble mean compared to observations. Most of the observed rainfall is found to be within the 10-90% confidence interval of the model data.

Overall, the weather@home model simulates the annual cycle of rainfall with satisfactory agreement, despite the dry monsoon rainfall bias. Furthermore, Rimi et al. (2019) shows that the weather@home model gives a reasonable representation of extreme rainfall events with return periods of 50-100 years. Therefore, we are confident that these biases will not affect our risk assessments for extreme rainfall events.

We have rewritten the paragraph with **lines 17- 31 in page 7** as: "The seasonal cycles of 5-day rainfall from the different model ensembles are adequately representative of the observed seasonal cycles. Most of the observed rainfall is found to be within the 10-90% confidence intervals of the model data. We find an early monsoon onset in the model simulations, which is also reported in previous studies (e.g., in Caesar et al., 2015; Fahad et al., 2017; Janes and Bhaskaran, 2012). However, JJAS rainfall is underestimated by 25-50% depending on the observational dataset and sub-regions. This bias is higher (up to 50% dry bias) in the wetter sub-regions of 2 and 4 (Figs. 1b & d) and lower (up to 30% dry bias) in the drier sub-regions of 1 and 3 (Figs. 1a & c). Underestimation of JJAS rainfall is reported in other model based studies over Indian monsoon region (Goswami et al., 2014; Kumar and Dimri, 2019; Saha et al., 2014) and specifically in Bangladesh (Caesar and Janes, 2018; Islam, 2009; Macadam and Janes, 2017). The bias is apparently present in all model scenarios used in this study; hence it is unlikely to affect the comparison between model scenarios. We also note that the signal of the change due to the changing climate is relatively small in comparison to the total rainfall. Therefore, the model is considered fit for purpose in assessing the potential impacts of climate change on extreme rainfall events."

Section 3.2: Impact of Climate Change and Aerosol Reduction on Seasonal Mean Rainfall

RC1: Provides important information regarding rainfall change due to warming 1.5˚C to 2˚C and aerosol impact. However, the change has been computed using model based on simulated observed data. The actual changes can be presented by using observation data (e.g., Aphrodite).

AC1: While it is definitely useful to look at the observed changes between pre-industrial and present-day rainfall, present day and future warmer (1.5 and 2.0 degrees) scenarios or the aerosol impacts; we can only do this kind of comparison using model simulated data. Because we have no high resolution gridded observational dataset that offers the pre-industrial records as well as the future scenarios of 1.5 and 2.0 degrees warming. APHRODITE data was only available from 1963 to 2007 at the time of writing this paper. Recently they have updated their data up to 2015. CPC observation dataset extends from 1979-present.

RC1: "While aerosol effects are consistent with other regions, the GHG induced rainfall is hampered, likely due to dynamic changes such as a delayed onset of the monsoon in response to warming", It can be supported with other relevant studies (e.g. the variation of interannual rainfall may depend on the onset of monsoon).

AC1: While it is beyond the scope of this study to identify the exact mechanisms that lead to future changes associated with aerosol removal (or the change due to contemporary emissions for that matter), we point to the literature where this issue has been investigated in some detail already. The seminal paper by Bollasina et al. (2011), as well as more recent work by Zhao et al. (2019) are excellent resources that support our point. We have added these two references to support this statement at **page 9 lines 13-14**.

3.3 Rainfall extreme:

Line 40, page7

RC1: "The signal-to-noise ratio is higher in the monsoon season across all sub-regions with the lowest and highest ratio in sub-region 1 and 3, respectively (Figs. 8a & 9a)". This statement may be needed further explanation.

AC1: This statement is rewritten at **page 9 lines 33-37** as "Overall, the signal-to-noise ratio is higher across all sub-regions, during JJAS compared to that during MAM. During MAM, the highest and lowest signal-to-noise ratio is over sub-region 1 and 3, respectively (Figs. 6a & 7a). On the other hand, during JJAS, we find the highest and lowest signal-to-noise ratio is over sub-region 3 and 1, respectively (Figs. 9a & 8a). The lower the ratio, the more difficult it is to establish causality as natural variability due to ENSO or circulation anomalies is higher."

References

RC1: The author referred Banglapedia, 2012 as citation in page 2 line 10. However, did not provide in the reference list.

AC1: We have now added this citation as "Banglapedia: River and Drainage system, Banglapedia- Natl. Encycl. Bangladesh [online] Available from: http://en.banglapedia.org/index.php?title=River_and_Drainage_System, 2012." in the revised bibliography. See **page 12 lines 4-5**

Other comments:

(a) The title of the paper says risks of seasonal extreme rainfall events and presented rainfall extreme using daily and five day mean rainfall. One day max and 5day max would be better presentation of rainfall extreme. It is also necessary to have a better description why daily and five day mean rainfall has been used.

AC1: This is because our focus is on unusual rare rainfall events with the potential to cause high impacts on the ground in pre-monsoon and monsoon seasons. We have used daily and 5-day running mean rainfall events throughout a season and then looked at events crossing a threshold (e.g. 250mm/day that can trigger floods or, landslides) with a high return period (e.g. 100 years). In particular, we have explored whether or not, and to what extent, the probability of having that same magnitude event (i.e. 250mm/day) changes in that particular season from one forcing scenario to another (e.g. from ACT to HAPPI 1.5).

An explanation for using 1 and 5-day rainfall is given at **page 5 lines 32-39**: "In Bangladesh 1- to 10-day high impact rainfall events can trigger flooding and landslides. For example, at north-east Bangladesh (sub-region 2), more than 150 mm MAM rainfall over a 6-day period can lead to an early flash flood (Ahmed et al., 2017). In contrast, at south-east Bangladesh (sub-region 4), more than 350 mm JJAS rainfall over a 3-day period is enough to cause a landslide (Ali et al., 2014). For a wide-spread river flooding e.g., the Brahmaputra River Basin flooding in August 2017, 10-day extreme rainfall event is considered (Philip et al., 2018). Considering such variations in rainfall magnitudes causing different hazards, we focused on daily and 5-day rainfall events to analyze the potential risks."

(b) Inconsistent in figure indexing spacing: In the results (e.g. Sect. 3.2) it is needed to be consistent with spacing when referencing to figures. For example, Fig.2 d and (Fig. 2d), (Figs. 8a & 8b) and (Fig. 4 a & c).

AC1: Figure indexing spacing issue has been resolved. Now this is uniformly done throughout the manuscript using Fig. 1a; Figs. 1a & b; Figs. 1a-d and Figs. 1b & 2b style.

(c) The Figure captions are too long. The author started to describe the results in some of them (e.g. Fig. 5). The results or discussion should be in text. Caption should be concise and just define what the Figure shows with the necessary information to gather information from it.

AC1: We have now moved parts of the figure captions to result and discussion section to reduce the length, and made them concise.

(d) Line 6 (page 4) – Evaluation of the model for the region was conducted by Rimi et al. (2019) and demonstrated a reasonable agreement between model results and observational datasets for extreme rainfall events. What is a reasonable agreement? Which statistical skills show general agreement (e.g. r2, KGE). For example, 60% of stations achieved values greater than 0.6 between modelled and observed data.

AC1: We present here Fig. AC1.a adapted from Rimi et al., (2019) for reference. In Figure AC1a., the black line represents the model simulated rainfall events; while, red, blue, orange and sky-blue colours indicate APHRODITE, GPCC, CPC gridded observations and TRMM satellite data respectively. Based on these figures, Rimi et al., (2019) reports that the pre-monsoon and monsoon extreme rainfall events with up to 100 years of return periods are adequately well captured by the model over Bangladesh when compared to APHRODITE, GPCC, CPC gridded observations and TRMM satellite data.

Although the observation data sets used in that model evaluation paper had short lengths of records; by fitting a Generalized Extreme Value distribution, the authors demonstrated that the model simulated extreme events are in good agreement with the observations.

In the revised manuscript we added the following lines at **page 4 lines 12-15**: “MAM and JJAS extreme rainfall events with up to 100 years of return periods are adequately well captured by the model over Bangladesh at local sub-regional scales when compared to high resolution gridded observation datasets as well as satellite data (Rimi et al., 2019a). The model is therefore considered to be fit for the purpose of assessing climate change impacts on extreme rainfall events under different forcing scenarios.”

RC1: The discussion article ‘Risks of seasonal extreme rainfall events in Bangladesh under 1.5 and 2.0degrees’ warmer worlds – How anthropogenic aerosols change the story’ by Ruksana H. Rimi et al. is very interesting focused on the extreme rainfall events due climate change particularly 1.5 and 2 degrees warmer world. This is a comprehensive analysis of future projection of multi model rainfall over several sub-region of Bangladesh. The author provides sufficient graphs and maps in the article which explained the results. The major findings of the article are related with the global warming and its implication extreme weather events for Bangladesh. Finally, I suggest that the author will consider the above comments in finalizing the script. The article is recommended to publish with minor correction.

AC1: The authors highly appreciate your careful review with constructive comments. We have updated the manuscript following most of your suggestions. In case of any disagreement, we have provided our explanation behind that. We hope that now the manuscript is ready to be accepted for publication.

References

Ahmed, M. R., Rahaman, K. R., Kok, A. and Hassan, Q. K.: Remote sensing-based quantification of the impact of flash flooding on the rice production: A case study over Northeastern Bangladesh, Sensors (Switzerland), 17(10), doi:10.3390/s17102347, 2017.

Ali, R. M. E., Tunbridge, L. W., Bhasin, R. K., Akter, S., Khan, M. M. H. and Uddin, M. Z.: Landslides susceptibility of chittagong city, bangladesh and development of landslides early warning system, in Landslide Science for a Safer Geoenvironment, vol. 1, pp. 423–429., 2014.

Allen, M.: Do-it-yourself climate prediction, Nature, 401(6754), 642, doi:10.1038/44266, 1999.

Banglapedia: River and Drainage system, Banglapedia- Natl. Encycl. Bangladesh [online] Available from: http://en.banglapedia.org/index.php?title=River_and_Drainage_System, 2012.

Bollasina, M. A., Ming, Y. and Ramaswamy, V.: Anthropogenic aerosols and the weakening of the south asian summer monsoon, Science (80-.)., 334(6055), 502–505, doi:10.1126/science.1204994, 2011.

Bollasina, M. A., Ming, Y. and Ramaswamy, V.: Earlier onset of the Indian monsoon in the late twentieth century: The role of anthropogenic aerosols, Geophys. Res. Lett., 40(14), 3715–3720, doi:10.1002/grl.50719, 2013.

Caesar, J. and Janes, T.: Regional climate change over South Asia, in Ecosystem Services for Well-Being in Deltas: Integrated Assessment for Policy Analysis, pp. 207–221., 2018.

Caesar, J., Janes, T., Lindsay, A. and Bhaskaran, B.: Temperature and precipitation projections over Bangladesh and the upstream Ganges, Brahmaputra and Meghna systems, Environ. Sci. Process. Impacts, 17(6), 1047–1056, doi:10.1039/C4EM00650J, 2015.

Chen, M., Shi, W., Xie, P., Silva, V. B. S., Kousky, V. E., Higgins, R. W. and Janowiak, J. E.: Assessing objective techniques for gauge-based analyses of global daily precipitation, J. Geophys. Res. Atmos., 113(4), doi:10.1029/2007JD009132, 2008a.

Chen, M., Xie, P. and NOAA Climate Prediction Center(CPC): CPC Gauge-Based Analysis of Global Daily Precipitation, in Western Pacific Geophysics Meeting, Cairns, Australia, 29 July - 1 August, 2008. [online] Available from: ftp://ftp.cpc.ncep.noaa.gov/precip/CPC_UNI_PRCP/GAUGE_GLB/DOCU/Chen_et_al_2008_Daily_Gauge_Anal.pdf, 2008b.

Chevuturi, A., Klingaman, N. P., Turner, A. G. and Hannah, S.: Projected Changes in the Asian-Australian Monsoon Region in 1.5°C and 2.0°C Global-Warming Scenarios, Earth's Futur., 6(3), 339–358, doi:10.1002/2017EF000734, 2018.

Donlon, C. J., Martin, M., Stark, J., Roberts-Jones, J., Fiedler, E. and Wimmer, W.: The Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) system, Remote Sens. Environ., 116, 140–158, doi:10.1016/j.rse.2010.10.017, 2012.

Endo, H., Kitoh, A., Ose, T., Mizuta, R. and Kusunoki, S.: Erratum: Future changes and uncertainties in Asian precipitation simulated by multiphysics and multi-sea surface temperature ensemble experiments with high-resolution Meteorological Research Institute atmospheric general circulation models (MRI-AGCMs) (Jo, J. Geophys. Res. Atmos., 118(5), 2303, doi:10.1002/jgrd.50267, 2013.

Essery, R. L. H., Best, M. J., Betts, R. A., Cox, P. M. and Taylor, C. M.: Explicit representation of subgrid heterogeneity in a GCM land surface scheme, J. Hydrometeorol., 4(3), 530–543, doi:10.1175/1525-7541(2003)004<0530:EROSHI>2.0.CO;2, 2003.

Fahad, M. G. R., Saiful Islam, A. K. M., Nazari, R., Alfi Hasan, M., Tarekul Islam, G. M. and Bala, S. K.: Regional changes of precipitation and temperature over Bangladesh using bias-corrected multi-model ensemble projections considering high-emission pathways, Int. J. Climatol., doi:10.1002/joc.5284, 2017.

Faust, E.: Rapid attribution: Is climate change involved in an extreme weather event?, [online] Available from: https://www.munichre.com/topics-online/en/2017/topics-geo/rapid-attribution, 2017.

Fung, F., Lopez, A. and New, M.: Water availability in +2 C and +4 C worlds, Philos. Trans. R. Soc. A Math. Phys. Eng. Sci., 369(1934), 99–116, doi:10.1098/rsta.2010.0293, 2011.

Goswami, B. B., Deshpande, M., Mukhopadhyay, P., Saha, S. K., Rao, S. A., Murthugudde, R. and Goswami, B. N.: Simulation of monsoon intraseasonal variability in NCEP CFSv2 and its role on systematic bias, Clim. Dyn., 43(9–10), 2725–2745, doi:10.1007/s00382-014-2089-5, 2014.

Guillod, B. P., Jones, R. G., Bowery, A., Haustein, K., Massey, N. R., Mitchell, D. M., Otto, F. E. L., Sparrow, S. N., Uhe, P., Wallom, D. C. H., Wilson, S. and Allen, M. R.: Weather@home 2: Validation of an improved global-regional climate modelling system, Geosci. Model Dev., 10(5), 1849–1872, doi:10.5194/gmd-10-1849-2017, 2017.

Guo, L., Highwood, E. J., Shaffrey, L. C. and Turner, A. G.: The effect of regional changes in anthropogenic aerosols on rainfall of the East Asian Summer Monsoon, Atmos. Chem. Phys., 13(3), 1521–1534, doi:10.5194/acp-13-1521-2013, 2013.

Gutro, R.: Bangladesh's Heavy Rainfall Examined With NASA's IMERG, Nasa Gpm [online] Available from: https://www.nasa.gov/feature/goddard/2017/bangladeshs-heavy-rainfall-examined-with-nasas-imerg (Accessed 14 November 2017), 2017.

Hauser, M., Gudmundsson, L., Orth, R., Jézéquel, A., Haustein, K., Vautard, R., van Oldenborgh, G. J., Wilcox, L. and Seneviratne, S. I.: Methods and Model Dependency of Extreme Event Attribution: The 2015 European Drought, Earth's Futur., 5(10), 1034–1043, doi:10.1002/2017EF000612, 2017.

Haustein, K., Uhe, P. F., Rimi, R. H., Islam, A. S. and Otto, F. E. L.: Is the wettest place on Earth getting wetter?, Geophys. Res. Lett., n.d.

Hossain, A. N. H. A.: Flood management. [online] Available from: http://www.apfm.info/publications/casestudies/cs_bangladesh_sum.pdf, 1998.

IPCC, 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. [online] Available from: http://scholar.google.nl/scholar?hl=nl&q=climate+change&btnG=&lr=&oq=climate+ca#2, 2013.

Islam, M. N.: Rainfall and Temperature Scenario for Bangladesh, Open Atmos. Sci. J., 3(1), 93–103, doi:10.2174/1874282300903010093, 2009.

Janes, T. and Bhaskaran, B.: Evaluation of regional model performance in simulating key climate variables over Bangladesh, Met Office, Exeter, United Kingdom., 2012.

Jones, A., Roberts, D. L., Woodage, M. J. and Johnson, C. E.: Indirect sulphate aerosol forcing in a climate model with an interactive sulphur cycle, J. Geophys. Res. Atmos., 106(D17), 20293–20310, doi:10.1029/2000JD000089, 2001.

Kirkevåg, A., Iversen, T., Seland, Ø., Hoose, C., Kristjánsson, J. E., Struthers, H., Ekman, A. M. L., Ghan, S., Griesfeller, J., Nilsson, E. D. and Schulz, M.: Aerosol–climate interactions in the Norwegian Earth System Model – NorESM1-M, Geosci. Model Dev., 6(1), 207–244, doi:10.5194/gmd-6-207-2013, 2013.

Klimont, Z., Smith, S. J. and Cofala, J.: The last decade of global anthropogenic sulfur dioxide: 2000-2011 emissions, Environ. Res. Lett., 8(1), doi:10.1088/1748-9326/8/1/014003, 2013.

Kripalani, R. H., Oh, J. H., Kulkarni, A., Sabade, S. S. and Chaudhari, H. S.: South Asian summer monsoon precipitation variability: Coupled climate model simulations and projections under IPCC AR4, Theor. Appl. Climatol., 90(3–4), 133–159, doi:10.1007/s00704-006-0282-0, 2007.

Kumar, D. and Dimri, A. P.: Sensitivity of convective and land surface parameterization in the simulation of contrasting monsoons over CORDEX-South Asia domain using RegCM-4.4.5.5, Theor. Appl. Climatol., doi:10.1007/s00704-019-02976-9, 2019.

Kumar, D., Arya, D. S., Murumkar, A. R. and Rahman, M. M.: Impact of climate change on rainfall in Northwestern Bangladesh using multi-GCM ensembles, Int. J. Climatol., 34(5), 1395–1404, doi:10.1002/joc.3770, 2014.

Kumar, K. K., Kamala, K., Rajagopalan, B., Hoerling, M. P., Eischeid, J. K., Patwardhan, S. K., Srinivasan, G., Goswami, B. N. and Nemani, R.: The once and future pulse of Indian monsoonal climate, Clim. Dyn., 36(11–12), 2159–2170, doi:10.1007/s00382-010-0974-0, 2011.

Lau, W. K. M. and Kim, K. M.: Fingerprinting the impacts of aerosols on long-term trends of the Indian summer monsoon regional rainfall, Geophys. Res. Lett., 37(16), n/a-n/a, doi:10.1029/2010GL043255, 2010.

Lee, D., Min, S.-K., Fischer, E. M., Shiogama, H., Bethke, I., Lierhammer, L. and Scinocca, J.: Impacts of half a degree additional warming on the Asian summer monsoon rainfall characteristics, Environ. Res. Lett., doi:10.1088/1748-9326/aab55d, 2018.

Li, Z., Lau, W. K. M., Ramanathan, V., Wu, G., Ding, Y., Manoj, M. G., Liu, J., Qian, Y., Li, J., Zhou, T., Fan, J., Rosenfeld, D., Ming, Y., Wang, Y., Huang, J., Wang, B., Xu, X., Lee, S. S., Cribb, M., Zhang, F., Yang, X., Zhao, C., Takemura, T., Wang, K., Xia, X., Yin, Y., Zhang, H., Guo, J., Zhai, P. M., Sugimoto, N., Babu, S. S. and Brasseur, G. P.: Aerosol and monsoon climate interactions over Asia, Rev. Geophys., 54(4), 866–929, doi:10.1002/2015RG000500, 2016.

Macadam, I. and Janes, T.: Validation of Regional Climate Model simulations for the DECCMA project, DECCMA Working Paper, Deltas, Vulnerability and Climate Change: Migration and Adaptation, IDRC Project Number 107642, www.deccma.com., 2017.

Massey, N., Jones, R., Otto, F. E. L., Aina, T., Wilson, S., Murphy, J. M., Hassell, D., Yamazaki, Y. H. and Allen, M. R.: Weather@Home-Development and Validation of a Very Large Ensemble Modelling System for Probabilistic Event Attribution, Q. J. R. Meteorol. Soc., 141(690), 1528–1545, doi:10.1002/qj.2455, 2015.

Menon, A., Levermann, A., Schewe, J., Lehmann, J. and Frieler, K.: Consistent increase in Indian monsoon rainfall and its variability across CMIP-5 models, Earth Syst. Dyn. Discuss., 4(1), 1–24, doi:10.5194/esdd-4-1-2013, 2013.

Mitchell, D., James, R., Forster, P. M., Betts, R. A., Shiogama, H. and Allen, M.: Realizing the impacts of a 1.5 °C warmer world, Nat. Clim. Chang., 6(8), 735–737, doi:10.1038/nclimate3055, 2016.

Mitchell, D., AchutaRao, K., Allen, M., Bethke, I., Beyerle, U., Ciavarella, A., Forster, P. M., Fuglestvedt, J., Gillett, N., Haustein, K., Ingram, W., Iversen, T., Kharin, V., Klingaman, N., Massey, N., Fischer, E., Schleussner, C. F., Scinocca, J., Seland, Ø., Shiogama, H., Shuckburgh, E., Sparrow, S., Stone, D., Uhe, P., Wallom, D., Wehner, M. and Zaaboul, R.: Half a degree additional warming, prognosis and projected impacts (HAPPI): Background and experimental design, Geosci. Model Dev., 10(2), 571–583, doi:10.5194/gmd-10-571-2017, 2017.

Murshed, S. B., Islam, A. K. M. and Khan, M. S. A.: Impact of climate change on rainfall intensity in Bangladesh, Dhaka, Bangladesh. [online] Available from: http://teacher.buet.ac.bd/akmsaifulislam/reports/Heavy_Rainfall_report.pdf, 2011.

National Academies of Sciences, Engineering, and M.: Attribution of Extreme Weather Events in the Context of Climate Change, National Academies Press, Washington, D.C., 2016.

Nirapad: Bangladesh: Flash Flood Situation - April 19, 2017, Situat. Rep., 7 [online] Available from: https://reliefweb.int/sites/reliefweb.int/files/resources/Flash_Flood%2C Updated %28April 19%29%2C 2017.pdf (Accessed 14 November 2017), 2017.

Nowreen, S., Murshed, S. B., Islam, A. K. M. S., Bhaskaran, B. and Hasan, M. A.: Changes of rainfall extremes around the haor basin areas of Bangladesh using multi-member ensemble RCM, Theor. Appl. Climatol., 119(1–2), 363–377, doi:10.1007/s00704-014-1101-7, 2015.

Otto, F. E. L.: Attribution of Weather and Climate Events, Annu. Rev. Environ. Resour., 42(1), 627–646, doi:10.1146/annurev-environ, 2017.

Paul, R. and Hussain, Z.: Landslide, floods kill 156 in Bangladesh, India; toll could rise, Reuters, 14th June [online] Available from: https://uk.reuters.com/article/uk-bangladesh-landslides/landslide-floods-kill-156-in-bangladesh-india-toll-could-rise-idUKKBN1950AG, 2017.

Philip, S., Sparrow, S., Kew, S. F., van der Wiel, K., Wanders, N., Singh, R., Hassan, A., Mohammed, K., Javid, H., Haustein, K., Otto, F. E. L., Hirpa, F., Rimi, R. H., Islam, A. S., Wallom, D. C. H. and van Oldenborgh, G. J.: Attributing the 2017 Bangladesh floods from meteorological and hydrological perspectives, Hydrol. Earth Syst. Sci. Discuss., 1–32, doi:10.5194/hess-2018-379, 2018.

Ramanathan, V., Chung, C., Kim, D., Bettge, T., Buja, L., Kiehl, J. T., Washington, W. M., Fu, Q., Sikka, D. R. and Wild, M.: Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle, Proc. Natl. Acad. Sci., 102(15), 5326–5333, doi:10.1073/pnas.0500656102, 2005.

Rawlani, A. K. and Sovacool, B. K.: Building responsiveness to climate change through community based adaptation in Bangladesh, Mitig. Adapt. Strateg. Glob. Chang., 16(8), 845–863, doi:10.1007/s11027-011-9298-6, 2011.

Rimi, R. H., Haustein, K., Barbour, E. J., Jones, R. G., Sparrow, S. N. and Allen, M. R.: Evaluation of a large ensemble regional climate modelling system for extreme weather events analysis over Bangladesh, Int. J. Climatol., 39(6), 2845–2861, doi:10.1002/joc.5931, 2019a.

Rimi, R. H., Haustein, K., Barbour, E. J. and Allen, M. R.: Risks of Pre-Monsoon Extreme Rainfall Events of Bangladesh: Is Anthropogenic Climate Change Playing a Role?, Bull. Am. Meteorol. Soc., 100(1), S61–S65, doi:10.1175/BAMS-D-18-0152.1, 2019b.

Saha, S. K., Pokhrel, S., Chaudhari, H. S., Dhakate, A., Shewale, S., Sabeerali, C. T., Salunke, K., Hazra, A., Mahapatra, S. and Rao, A. S.: Improved simulation of Indian summer monsoon in latest NCEP climate forecast system free run, Int. J. Climatol., 34(5), 1628–1641, doi:10.1002/joc.3791, 2014.

Samset, B. H., Sand, M., Smith, C. J., Bauer, S. E., Forster, P. M., Fuglestvedt, J. S., Osprey, S. and Schleussner, C. F.: Climate Impacts From a Removal of Anthropogenic Aerosol Emissions, Geophys. Res. Lett., 45(2), 1020–1029, doi:10.1002/2017GL076079, 2018.

Schaller, N., Kay, A. L., Lamb, R., Massey, N. R., Van Oldenborgh, G. J., Otto, F. E. L., Sparrow, S. N., Vautard, R., Yiou, P., Ashpole, I., Bowery, A., Crooks, S. M., Haustein, K., Huntingford, C., Ingram, W. J., Jones, R. G., Legg, T., Miller, J., Skeggs, J., Wallom, D., Weisheimer, A., Wilson, S., Stott, P. A. and Allen, M. R.: Human influence on climate in the 2014 southern England winter floods and their impacts, Nat. Clim. Chang., 6(6), 627–634, doi:10.1038/nclimate2927, 2016.

Schleussner, C. F., Lissner, T. K., Fischer, E. M., Wohland, J., Perrette, M., Golly, A., Rogelj, J., Childers, K., Schewe, J., Frieler, K., Mengel, M., Hare, W. and Schaeffer, M.: Differential climate impacts for policy-relevant limits to global warming: The case of 1.5 °c and 2 °c, Earth Syst. Dyn., 7(2), 327–351, doi:10.5194/esd-7-327-2016, 2016.

Shahid, S.: Rainfall variability and the trends of wet and dry periods in Bangladesh, Int. J. Climatol., 30(15), 2299–2313, doi:10.1002/joc.2053, 2010.

Srivastava, A., Naresh Kumar, S. and Aggarwal, P. K.: Assessment on vulnerability of sorghum to climate change in India, Agric. Ecosyst. Environ., 138(3–4), 160–169, doi:10.1016/j.agee.2010.04.012, 2010.

Stainforth, D. A., Aina, T., Christensen, C., Collins, M., Faull, N., Frame, D. J., Kettleborough, J. A., Knight, S., Martin, A., Murphy, J. M., Piani, C., Sexton, D., Smith, L. A., Splcer, R. A., Thorpe, A. J. and Allen, M. R.: Uncertainty in predictions of the climate response to rising levels of greenhouse gases, Nature, 433(7024), 403–406, doi:10.1038/nature03301, 2005.

Stark, J. D., Donlon, C. J., Martin, M. J. and McCulloch, M. E.: OSTIA: An Operational, high resolution, real time, global sea surface temperature analysis system., in Oceans 2007 - Marine Challenges: Coastline to Deep Sea, pp. 1–4, IEEE., 2007.

Stott, P. A., Stone, D. A. and Allen, M. R.: Human Contribution to the Heat wave of 2003, Nature, 432(7017), 610–614, 2004.

The World Bank: Turn Down Heat: Why a 4 degree warmer world must be avoided. A Report for the World Bank by the Potsdam Institute for Climate Impact Research and Climate Analytics, Washington, DC : World Bank. [online] Available from: http://climatechange.worldbank.org/sites/default/files/Turn_Down_the_heat_Why_a_4_degree_centrigrade_warmer_world_must_be_avoided.pdf, 2012.

Turner, A. G. and Annamalai, H.: Climate change and the South Asian summer monsoon, Nat. Clim. Chang., 2(8), 587–595, doi:10.1038/NCLIMATE1495, 2012.

UNFCCC: Paris Agreement, in 21st Conference of the Parties, vol. 2017, p. 3., 2015.

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J. F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J. and Rose, S. K.: The representative concentration pathways: An overview, Clim. Change, 109(1), 5–31, doi:10.1007/s10584-011-0148-z, 2011.

Wang, B., Liu, J., Yim, P. J. W. S. and Kiefer, T.: Recent change of the global monsoon precipitation (1979 – 2008), Clim. Dyn., 39(5), 1123–1135, doi:10.1007/s00382-011-1266-z, 2012.

Wilks, D. S.: Comparison of three- parameter probability distributions for representing annual extreme and partial duration precipitation series, Water Resour. Res., 29(10), 3543–3549, doi:10.1029/93WR01710, 1993.

Wilks, D. S.: Statistical Methods in the Atmospheric Sciences, Academic Press, 2011., 2011.

Yatagai, A., Kamiguchi, K., Arakawa, O., Hamada, A., Yasutomi, N. and Kitoh, A.: Aphrodite constructing a long-term daily gridded precipitation dataset for Asia based on a dense network of rain gauges, Bull. Am. Meteorol. Soc., 93(9), 1401–1415, doi:10.1175/BAMS-D-11-00122.1, 2012.

Zhao, A.D., Stevenson, D.S. and Bollasina, M.A., The role of anthropogenic aerosols in future precipitation extremes over the Asian Monsoon Region, Climate Dynamics 52:6257-6278, doi: 10.1007/s00382-018-4514-7, 2019

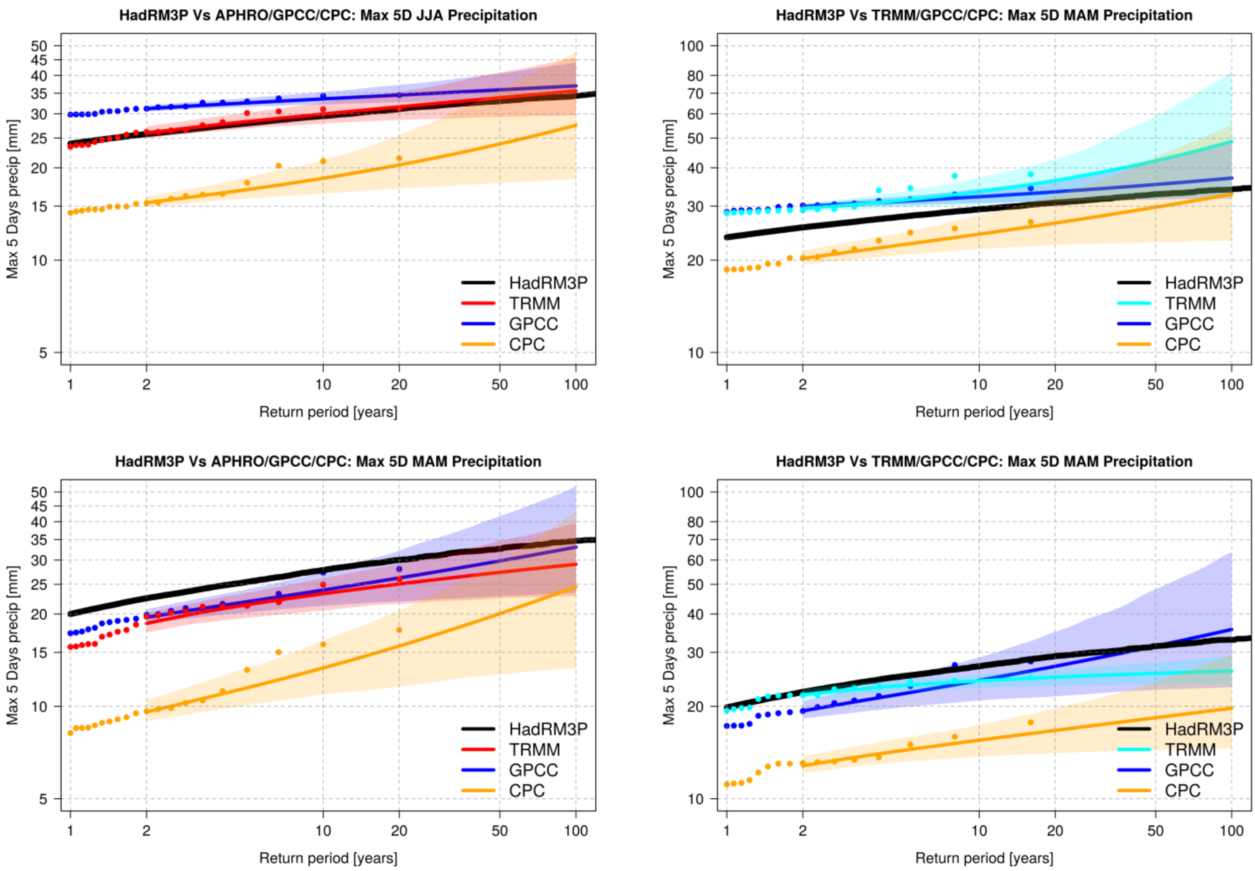

Figure AC1.a: Left panels show 5-day rainfall events in JJA and MAM over Bangladesh while right panels show the same but for sub-region 2. The black line is for the model simulated events, while, red, blue, orange and sky-blue colours indicate APHRODITE, GPCC, CPC gridded observations and TRMM satellite data respectively.

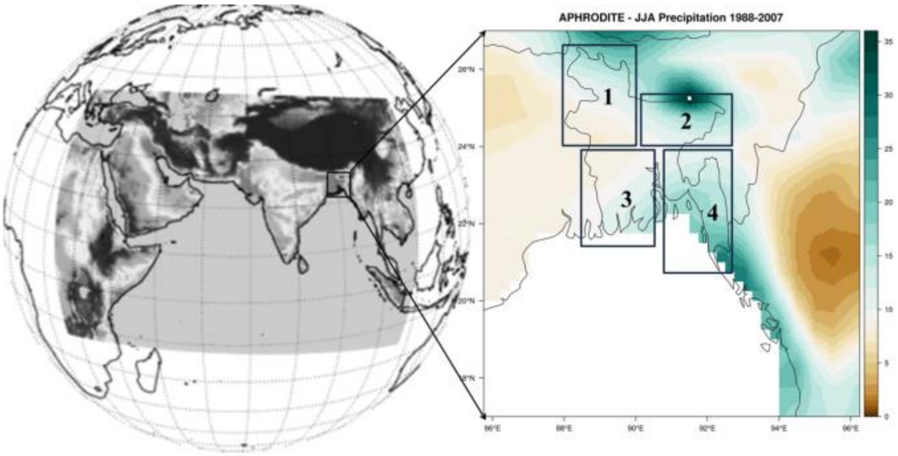

Figure AC1.b: Left panel shows South Asia domain of the weather@home regional climate model and right panel shows the four sub-regions of Bangladesh with APHRODITE based mean monsoon rainfall (mm/day).

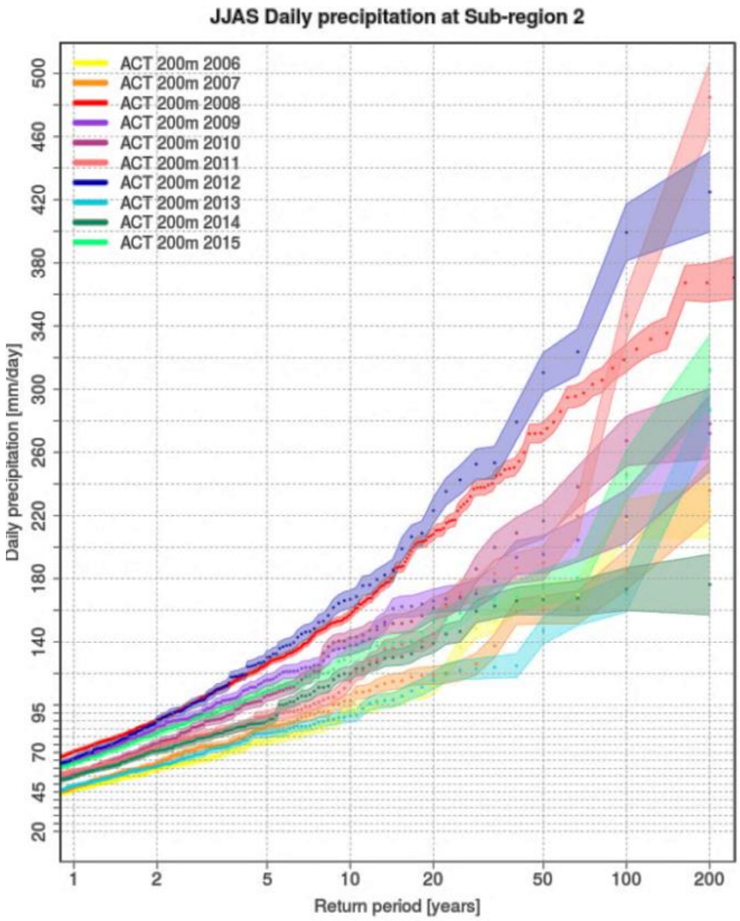

Figure AC1.c: Return period plots for JJAS daily precipitation over sub-region 2 in different years (2006-2015).

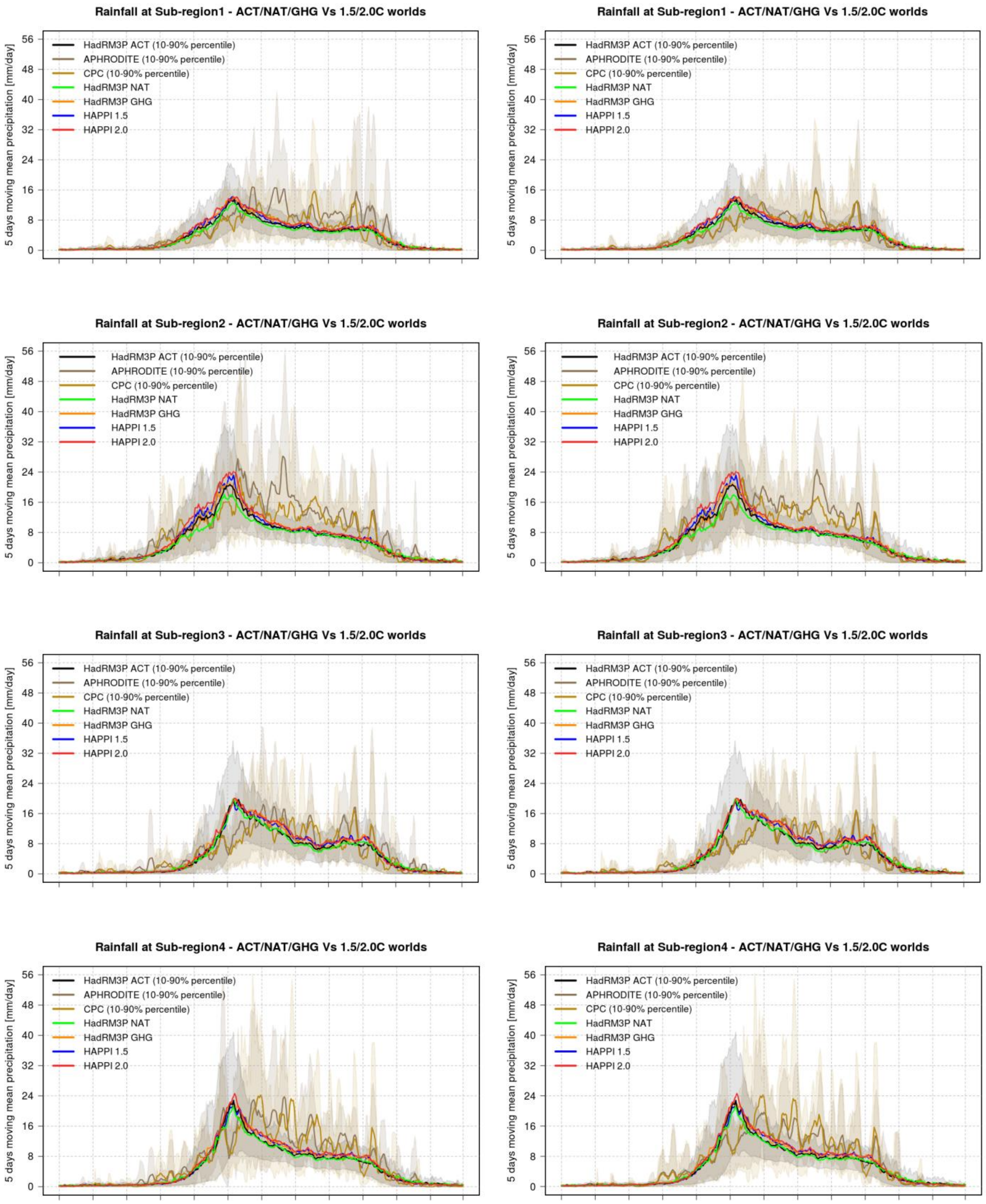

Figure AC1.d: The left column shows the old version of the annual cycles of 5-day rainfall over the four sub-regions of Bangladesh. The right column shows the same but uses updated APHRODITE data.

We thank for the constructive comments from the anonymous Reviewer 2. We have carefully revised the manuscript to incorporate necessary amendments as per suggestions. Responses to the Referee Comments 2 (RC2) are presented in the following Author's Comments 2 (AC2):

The authors investigate changes in mean and extreme precipitation in Bangladesh for five different forcing scenarios. They divide Bangladesh in four regions and analyse the magnitude of events with different return times. They find increases in pre-monsoon and monsoon precipitation due to higher global mean temperatures but also due to a decrease in aerosols. While the paper is clear in scope and the analysis in principle straightforward, it needs more work, especially the text. As crucial information is missing from the methods section I can only recommend publication of the paper after major revisions.

General and Technical Comments

Text

RC2: The text could profit from more work. Some sections seem rather long; while others miss some essential information (see below). Also, there are numerous small mistakes that give the impression of sloppy proofreading. The conclusions, on the other hand are very well written and concise.

AC2: Thank you for your careful review. We have revised the text as per suggestions and corrected the identified errors in the text.

RC2: It is very hard to really pin down, but I had the impression that some information is repeated over and over again, see e.g. my comment concerning the abbreviations below. Another example is the first two sentences in your introduction - they are different but they basically say the same. Of course, sometimes it is good to repeat things (e.g. in the conclusions), I felt it rather hindered the flow while reading.

AC2: We have aimed at avoiding repetitions in the manuscript as good as possible now.

RC2: When you use the word significant do you mean 'statistically significant' or large? Significant is a reserved word – please only use it if you conducted a statistical test!

AC2: We mean statistically significant here. For all risk ratios, we also have calculated the associated error bars (using bootstrapping) to know whether the results are statistically significant or not.

RC2: Similarly, you have to be careful when using the word 'risk'. Risk is often formalized as the combination of exposure and vulnerability to weather and climate events. Therefore please check if 'probability' of 'magnitude' would be more appropriate.

AC2: We are aware that 'risk' is often defined as the product of vulnerability and exposure. However, in the probabilistic event attribution, ‘risk’ is indicative of the range of hazards. According to UNFCCC, “Climate related risks are created by a range of hazards. Some are slow in their onset (such as changes in temperature and precipitation leading to droughts, or agricultural losses), while others happen more suddenly (such as tropical storms and floods).” [Source: https://unfccc.int/topics/resilience/resources/climate-related-risks-and-extreme-events]. In the abstract **(See page 1 line 13)**, to avoid any possibility of misinterpretation, we have added an explanation for the term ‘risk’.

RC2: You introduce abbreviations for the simulations, but you often refer to the simulations by the full name; e.g. on P6: L11 (twice); L15, L16, L21; L30 (twice). There are many more examples throughout the manuscript.

AC2: Apologies for the irregularity. The model simulations are now uniformly denoted throughout the manuscript.

RC2: What is the abbreviation for the simulation with current-day GHGs and pre-industrial aerosols? GHGonly? GHG? GHG only? AR? All of them are used throughout the manuscript. Be consistent! Also make sure that it can be differentiated from the abbreviation for greenhouse gas (GHG).

AC2: Apologies again for such inconsistency. In this model ensemble, anthropogenic aerosols are reduced to pre-industrial levels, and so, the GHGs (at current concentrations) act as the main forcing. Hence this model ensemble consists of ACT GHGs with reduced anthropogenic aerosols (levels of the natural aerosols are unchanged). To keep this uniform throughout the manuscript, this model ensemble is now called ‘GHG-only’.

Methods

RC2: You should explicitly write why you use different time periods for your two observational datasets.

AC2: At the time of analysing data for this study, APHRODITE was only available until 2007; while, CPC was available for the period of 2006-2015. Fortunately, this APHRODITE data is recently updated up till 2015. Therefore, we have updated our analysis with same period for all model and observation data sets.

RC2: You use bi-linear interpolation to regrid your data. For the future I would recommend to use a conservative remapping scheme to make sure the precipitation amount is conserved.

AC2: Thank you for the suggestion. We have checked ACT precipitation data over Bangladesh in this regard. As per figure AC2.a, we can argue that changing the method from bilinear interpolation to conservative has no effect on the high intensity precipitation events.

RC2: The description of the model simulations is very long and overly detailed. I recommend to shorten it.

AC2: We have tried to make this part shorter by avoiding repeating ensemble information.

RC2: On the other hand, I miss a description of your statistical analysis, which makes it difficult to assess it. In particular I need the following questions answered:

RC2: How do you calculate the return time?

AC2: "Return time" of an event, also known as the "return period" is the likelihood of an event occurring, defined by a particular variable exceeding a certain threshold during a given time interval. For a variable *X*, if the threshold level is x_T, then an extreme event occurs when $X \geq x_T$

Now, if *p* is the probability of occurrence of an extreme event, then Return Period $E(\tau) = T = 1/p$, *or*, $p(X \geq x_T) = 1/T$. For instance, a "1 in 10 year event" is an event with a 10% chance of occurring. On the contrary, the rarest event is a "1 in 1000 year event", with a 0.1% chance of occurring in a given year.

RC2: How do you calculate the uncertainty of the return time?

AC2: The uncertainty of the return period is calculated using bootstrapping. The time series is resampled a 1000 times and what we present are the 95% confidence intervals. We note that structural model uncertainty (such as parameter sensitivity) is not included in our uncertainty estimate.

We have explained the calculation method for Return Time and its Uncertainty in **page 6 lines 1-10** of the revised manuscript as: ""Return time" of an event, also known as the "return period" is the likelihood of an event occurring, defined by a particular variable exceeding a certain threshold during a given time interval. If variable X is equal to or greater than an event of magnitude x_T, occurs once in T years, then the probability of occurrence $P(X \geq x)$ in a given year of the variable is (Wilks, 2011):

$$P(X \geq x = \frac{1}{T}) \text{ or, } T = \frac{1}{1-P(x \geq x_T)}$$

A "1 in 10 year event" is an event with a 10% chance of occurring. On the contrary, the rarest event is a "1 in 1000 year event", with a 0.1% chance of occurring in a given year. The rainfall amounts associated with the 50- or 100-year return periods are extracted from the 98^{th} and 99^{th} percentiles, respectively, of a fitted distribution (i.e., $[1–0.98^{-year}]^{-1}$ = 50 years and $[1–0.99^{-year}]^{-1}$ =100 years) (Wilks, 1993). The uncertainty of the return period is calculated using bootstrapping method. The time series of each ensemble is resampled a 1000 times using bootstrapping to derive 5 to 95% confidence intervals for return periods. We note that structural model uncertainty (such as parameter sensitivity) is not included in our uncertainty estimate."

RC2: For the RR, do you assume an Extreme Value distribution? If not how is the probability calculated?

AC2: In case of the model results, we have large enough an ensemble to calculate the probabilities of occurrence (P) of the event in question explicitly by means of the different forcing scenarios. For example, suppose a 200 mm/day precipitation event has a P_{actual} of 50 years and a $P_{natural}$ of 100 years. The resulting change of probability of that event would simply be a doubling (RR= 2) due to the change in forcing.

RC2: How do you calculate the uncertainty of RR?

AC2: To calculate the upper and lower limits of the uncertainty of RR we have used the following formula (based error propagation model for independent contributors):

Upper limit of RR uncertainty = $\sqrt{}(a^2 + c^2)$; and Lower limit of RR uncertainty = $\sqrt{}(b^2 + d^2)$

Where, a = upper limit of uncertainty of P_{ACT}, b = lower limit of uncertainty of P_{ACT},

c = upper limit of uncertainty of P_{NAT}, d = lower limit of uncertainty of $P_{NAT.}$

We have added these responses in the revised manuscript in **page 7 line 1-9.**

RC2: Do you consider all days or only days with rainfall larger a threshold? This is particularly relevant for MAM.

AC2: We are considering all days while calculating the return periods. In this way, we can look at low intensity rainfall events with minimum return period of 1 year, and also high intensity rainfall events with up to 980 years return period. However, we focused on rainfall events with high return periods that are relevant for impacts and adaptation planning (e.g., 10-100 year events).

*RC2: Given that you have data from 98 * 10 years, should your maximum return time not be at 980 years instead of 1000 as in Figure 6?*

AC2: The maximum return period is at 980 years. The coloured dots in the figure end at that point but the scale ends at 1000 years. Due to very little difference between them (in comparison to the total length of the scale), it is not clearly visible. We have updated all return time plots with rainfall events with 10-100 year return period because these events are particularly relevant for impact assessments and adaptation planning.

RC2: Similarly, when analysing the two wettest/ driest years should you not end at 196 years instead of 200?

AC2: Yes, you are right. This ends at 196 years not 200 years.

RC2: You might want to mention that you look at SPI in the methods.

AC2: SPI calculation method is now added to the supplementary material of the manuscript.

Results

RC2: The two observational datasets show quite some differences. Do you have a guess if this is due to the different periods they span, or would they also be different covering the same periods? How different are they during the two overlapping years?

AC2: The discrepancy between the two observation data sets is due to different periods that they spanned. We have now used the same time period for both data sets because APHRODITE is recently updated and this data version covered up till 2015. Figure AC2.b demonstrates the improvement in the results; by comparing the old and updated versions of the annual cycles. In the right panels we can see, that the two observation data sets are in better agreement. The model biases are also reduced as a consequence of comparison between the model and observation data spanning the same time period.

RC2: What is the point of using the two lowest and highest years? It basically says 'during a wet year the magnitude of a 1 in X year's event is larger than during an average year', which is a relatively trivial result. Also, these results are barely used / described in the results sections. My proposition would be to either remove this entirely, or move it to the appendix. This would help to clean up the figures and/ or reduce the amount of required subplots.

AC2: The use of two wettest and driest years explains how much natural variability of sea surface temperatures (SSTs) contributes to the variability of rainfall intensities over this study area. These are two pairs of individual years with the wettest and driest conditions amongst all model years of ACT ensemble. This model ensemble has same forcings in each year for the historical period of 2006-2015 and this means the only variability playing a role in changing the intensity of rainfall is natural variability of SSTs. This indicates that for Bangladesh natural SST variability can play a role besides the anthropogenic forcings in some cases. This would not be the same case, for example, in a European country context, where natural variability of SSTs would be very small and so it will have minimal contribution compared to other forcings. We agree that this result is not adequately discussed in the manuscript and so we are adding this in the updated version.

See **page 9 lines 29-33** for the added information as: "Overall, the signal-to-noise ratio is higher across all sub-regions, during JJAS compared to that during MAM. During MAM, the highest and lowest signal-to-noise ratio is over sub-region 1 and 3, respectively (Figs. 6a & 7a). On the other hand, during JJAS, we find the highest and lowest signal-to-noise ratio is over sub-region 3 and 1, respectively (Figs. 9a & 8a). The lower the ratio, the more difficult it is to establish causality as natural variability due to ENSO or circulation anomalies is higher."

RC2: Evaluation is done with 5-day precipitation but return time plots and RR in the main text are with 1-day precipitation – why is that?

AC2: For model evaluation, 5-day running mean precipitation based seasonal cycles only smooths out the variability of daily data based seasonal cycles (not shown) – the overall model evaluation result remains the same. For brevity, we only put the 5-day precipitation based annual cycles in the manuscript. For RRs, we have looked at both 1- and 5-day precipitation events considering their potential to cause flash floods or, landslides. We have presented 1-day precipitation based RRs in the main text because (i) this illustrates the highest variability of the daily precipitation extremes that are probable due to different forcings (ii) daily extreme precipitation events can have sudden and severe impacts on society by affecting agriculture, transport, industry and ecosystem services. The return period plots for 5-day precipitation events are presented at the supplementary materials.

RC2: You sometimes talk about a linear rainfall response. What do you mean with linear? How can you know it's linear (as you have only 5 data points)?

AC2: By linear response, we meant steady and gradual increase in the climate change impact on rainfall from one forcing scenario to another due the warming effects starting from NAT to ACT, ACT to HAPPI 1.5 and HAPPI 1.5 to HAPPI 2.0. But we see a non-linear response during JJAS (in Fig. 3) which involves a drying effect from pre-industrial to present climate (Fig. 3a), followed by a large wetting effect from present-day climate to 1.5 degrees warmer world (Fig. 3b) but then again a small wetting effect from 1.5 to 2.0 degrees warmer worlds (Fig. 3c). If we consider the GHG-only scenario, we can explain this non-linear effect, as it demonstrates the extent of aerosol-related rainfall suppression (Fig. 3d). The "data points" are the result of hundreds of model simulations, i.e. they are robust as far as our weather@home model setup is concerned. They might differ amongst models, but since the other HAPPI models do not provide a GHG-only scenario, we can only infer causality of potential non-linear changes between the warming scenarios from weather@home.

We have explained the term linear response in the revised manuscript in **page 8 lines 7-9** by adding the lines**: "**By linear response, we meant steady and gradual increase in the climate change impact on rainfall from one forcing scenario to another due the warming effects starting from NAT to ACT, ACT to HAPPI 1.5 and HAPPI 1.5 to HAPPI 2.0."

RC2 General Comments on Figures

*RC2: I had to rasterize the Figures in order to print them. Not sure what the problem is but - please make sure this does not happen for the final paper. However, even in your original pdf the figures are all blurry and don't have a good quality, this makes them very difficult to analyse. Please save them as *.pdf and ensure fonts are embedded.*

AC2: Apologies for the difficulties that you have faced. Most of the figures are redone to have good quality with high resolution.

RC2: Avoid mixing green and red in the figures.

AC2: Thank you, this point is noted.

RC2: The text (labels, legend) is generally too small.

AC2: Labels, legends are now larger where possible.

RC2: The captions are very long and describe results. Please make them shorter and move all results to the main text.

AC2: The captions are made reasonably shorter by moving some texts to main results section.

RC2: The naming of simulations is inconsistent in the legend/ labels. E.g. in Figure 1 you call it 'HadRM3P ACT' but 'HAPPI 2.0'. I recommend removing 'HadRM3P'. In Figure 2 and 3 it is called present instead of ACT. In Figure 4 you introduce a new abbreviation!

AC2: Removed HadRM3P, its only ACT now. We have now used uniform names throughout the manuscript for the different forcing scenarios. ACT, NAT, GHG-only, HAPPI 1.5 and HAPPI 2.0 are used for present-day actual; pre-industrial natural; present-day GHG (with pre-industrial levels of anthropogenic aerosols); and additional global warming since pre-industrial period by 1.5 and 2.0 degrees, respectively.

RC2: In the same category: sometimes it is called MAM and sometimes pre-monsoon

AC2: Now they are kept uniform throughout the manuscript.

RC2 Specific Comments on Figures

RC2: Figure 1: Annual -> seasonal

AC2: Amended as per suggestion.

RC2: Figures 2 and 3: I recommend to change the title to '(ACT - NAT) / NAT', '(HAPPI1.5 – ACT) / ACT', etc. so it is absolutely clear what you are doing.

AC2: Percent change (PC) is calculated as: $PC_{\text{actual relative to natural}} = \{(ACT\text{-}NAT)/ACT\} \times 100$. We have added a paragraph explaining how PC is calculated in the supplementary material. Therefore, we are not changing the figure caption.

RC2: The maps in the top row look a bit distorted – do you use a projection for the map plot?

AC2: The maps are produced again with high resolution and without any distortion. We show here one updated figure to show the improvements.

RC2: Why is it only 'approximately' the sub-regions? Remove approximately.

AC2: Removed

Figure 6: 'sub-regions of 1 and 2' -> remove of

AC2: Removed

RC2: Figures 10 and 11: Please use a logarithmic y-axis so that the plot is symmetric with respect to 1. Remove the bars, the RR is not really something that starts a 0. Reverse the order of the bars, start with the 1 in 10 year event.

AC2: We have now used a logarithmic y-axis. After using a logarithmic y-axis, the issue of starting from 0 is solved. The order of the bars is reversed starting from 10 in 100-year event. See the updated figures AC2. c, & d).

RC2 Minor Comments

RC2: P1 L11: the future

AC2: Amended

RC2: P1 L15: risk -> probability

AC2: We want to keep the term as it is. To avoid any possibility of misinterpretation, we have explained clearly what the term 'risk' means in this study.

RC2: P1 L16: 2C global warming

AC2: We want to keep it as it is because this is an opening statement and so it can be applicable for 1, 2, 3 or even 4 degrees warmer conditions. But we have only focused on the Paris Agreement temperature targets.

RC2: P1 L20: risk -> probability or magnitude

AC2: We want to keep the term as it is. To avoid any possibility of misinterpretation, we have now explained clearly what the term 'risk' means in this study.

RC2: P1 L23: in terms : : : impact. -> remove, you do not look at impacts

AC2: By impacts we meant climate change impacts on the probabilities of extreme rainfall events. We have modified the line as "Climate change impacts on the probabilities of extreme rainfall events are found during both pre-monsoon and monsoon seasons, but the level of impacts are spatially variable across the country."

RC2: P1 L25: GHG abbreviation not introduced

AC2: GHG abbreviation is now introduced.

RC2: P2 L12: Is it really an increasing trend – do you mean a positive trend?

AC2: We meant a positive trend. This line is now changed to "The frequencies of observed high-intensity rainfall events are increasing in the recent years."

RC2: P2 L14: names -> name

AC2: Corrected

RC2: P2 L15: Currently the sentence reads as if the "low-lying areas" damaged the rice.

AC2: Modified the line at **page 2 lines 22-23** as "Consequently, vast areas of Haors (local name for lowland wetlands) and low-lying areas were inundated and most of the nearly-harvestable 'Boro' paddy crop (a local high yielding variety of paddy) was damaged (Nirapad, 2017)."

RC2: P2 L15: Should that be "Boro (...) and paddy crops"? Or is should it be "Boro paddy crops (...)"?

AC2: It should be Boro paddy crop (….), see the above response.

RC2: P2 L16: Which dataset is this?

AC2: It is NASA's Integrated Multi-satellitE Retrievals for Global Precipitation Measurement, GPM (IMERG) data. We have now mentioned this in the manuscript at **page 2 lines 24-25.**

RC2: P2 L25: remove 'multi'. Also I would recommend to rewrite this sentence.

AC2: 'multi' is removed and the sentence is re-written as follows: "According to global climate model (GCM) ensemble based study, By 2090, the north-western part of Bangladesh would experience ~9% and ~18% increase in the pre-monsoon (Mar-May) and monsoon (Jun-Sep) mean rainfall respectively (Kumar et al., 2014)". See **page 2 lines 34-36.**

RC2: P2 L25: for the northwestern part of

AC2: This part is edited, see the above response.

RC2: P2 L27: the high resolution

AC2: Amended

RC2: P2 L28: in the global

AC2: Amended

RC2: P2 L31: north-eastern

AC2: Amended

RC2: P2 L34: remove 'of'

AC2: Removed 'parts of'

RC2: P2 L35: Even if they did not calculate RRs other studies did look at the influence of anthropogenic climate change -> please reformulate

AC2: By the influence of anthropogenic climate change, we meant the human impacts on climate change due to past GHG emissions (since pre-industrial period). This attribution experiment is done by comparing probabilities of occurrences of events crossing a predefined threshold in (i) present-day climate and (ii) a hypothetical natural climate with pre-industrial levels of GHGs in the atmosphere. This is certainly not done in Kumar et al., (2014), Caesar et al., (2015), and Nowreen et al., (2015). For clarity, we have changed the line as "...; explained whether or not anthropogenic climate change played a role in changing the probabilities of those projected future rainfall events; …..." in **page 2, line 43 to page 3 line1**.

RC2: P2 L41: runs -> simulations

AC2: Amended as per suggestion.

RC2: P2 L41: remove 'the'

AC2: Removed

RC2: P3 L4-L5: also : : : warning: I don't understand what you mean here.

AC2: These observation data sets are also used in another paper of the authors. We have removed this line to avoid confusion.

RC2: P3 L10: remove 'here'

AC2: Removed

RC2: P3 L11-L14: I recommend to move this sentence to the methods.

AC2: Agreed and moved to method section.

RC2: P3 L18: 2.2 -> 3.1

AC2: Corrected, thank you for pointing this out.

RC2: P3 L20: You did not mention Section 3.2

AC2: Section 3.2 is now mentioned.

RC2: P3 L27: remove the second 'observational'

AC2: Removed

RC2: P3 L30: remove 'grids'

AC2: Removed, this line is rewritten as "APHRODITE is a high-resolution daily gridded rainfall data set for Asia (V1901, available for 1998-2015); created primarily with data obtained from a rain-gauge-observation network." See **page 3 lines 33-34.**

RC2: P3 L31: in Table S1

AC2: Corrected

RC2: P3 L39: Move the reference behind 'program'.

AC2: Moved as per suggestion

RC2: P3 L41: remove 'of'

AC2: Removed

RC2: P4 L2: remove 'the model'

AC2: Removed

RC2: P4 L5: GHG was introduced before

AC2: It is 'GHG-only' not 'GHG'.

RC2: P4 L6-L9: This belongs in the Results Section.

AC2: Moved to Result section

RC2: P4 L10: remove ‘the’

AC2: Removed

RC2: P4 L27: one third

AC2: Amended as per suggestion.

RC2: P4 L29: remove ‘world’

AC2: Removed

RC2: P4 L31: hereinafter?

AC2: Removed hereinafter

RC2: P4: Formula (i) and (ii): These are unnecessary.

AC2: Removed

RC2: P4 L39: force -> forcing

AC2: Amended as per suggestion.

RC2: P4 L41: the other GCMs -> other GCMs

AC2: Amended as per suggestion.

RC2: P5 L5 and L6: I would write this as 3x30x10x98 and 4x30x10x98. In addition, make a remark that all months have 30 days in the used model.

AC2: Agreed and rewritten as per suggestion; see **page 6 lines 15-17**.

RC2: P5 L15: presented -> present

AC2: Amended as per suggestion.

RC2: P5 L15: This sentence does not make sense, please rewrite.

AC2: Rewritten as "In order to quantify changes in the probability of occurrence of extreme rainfall event, we use Risk Ratio (RR), which is calculated as RR = Pf / Pcf (NAS, 2016). Here Pf denotes the probability of the event in factual climate including climate change (ACT, HAPPI 1.5 and HAPPI 2.0) and Pcf denotes the probability of an event of the same magnitude in a counterfactual climate without anthropogenic climate change (NAT)." see **page 6 lines 36-39**.

RC2: P5 L17: the probability

AC2: Amended as per suggestion.

RC2: P5 L17: remove 'scenarios'

AC2: Removed

RC2: P5 L18: an event of the same magnitude

AC2: Amended as per suggestion.

RC2: P5 L18-L20: Abbreviations!

AC2: Rewritten

RC2: P5 L26 and L34: annual -> seasonal

AC2: Amended as per suggestion.

RC2: P5 L35: dataset it is compared with and sub-regions. -> dataset and the sub-region.

AC2: Amended as per suggestion.

RC2: P5 L36: at -> in

AC2: Amended as per suggestion.

RC2: P5 L36: There is no way to know if the bias is the same for the different scenarios! This is an assumption. It's ok to make the assumption, but 'note' is not the appropriate word here.

AC2: Removed the word 'note' and rewritten the sentence as "The bias is apparently present in all model scenarios; hence it is unlikely to affect the comparison between model scenarios". See **page 7 line 26**.

RC2: P6 L2: Significant?

AC2: Yes, ‘significant’ because the changes in seasonal mean rainfall are calculated from the result of hundreds of model simulations, i.e. they are robust as far as our weather@home model setup is concerned.

RC2: P6 L6: although they suggest

AC2: Amended as per suggestion.

RC2: P6 L28-L29: Did you show this somewhere in your paper? Do you have a reference for this?

AC2: We refer to Bollasina at al. (2011) and Zhao et al. (2019) for more theoretical background and model support for our conjecture (which we do not further analyse as it is beyond the scope of this paper) that circulatory changes may have caused the non-linear rainfall percent-change in northern India with warming.

RC2: P6 L34-L35: Is that global or local warming?

AC2: It is global, not local warming. We are looking at global warming effects on regional/local weather events.

RC2: P6 41: Significant?

AC2: yes, it refers to ‘significant impacts’.

RC2: P7 L4: remove ‘and hence efficiently masked’

AC2: Removed

RC2: P7 L6: SPI: abbreviation not introduced

AC2: Now it is introduced. See **page 8 line 34-35**

RC2: P7 L15: in all -> in almost all

AC2: Amended as per suggestion

RC2: P7 L36: frequencies of occurrence -> magnitude

AC2: Amended as per suggestion

References:

Bollasina, M.A., Ming, Y. and Ramaswamy, V.: Anthropogenic Aerosols and the Weakening of the South Asian Summer Monsoon, Science 334 (6055), 502-505, doi: 10.1126/science.1204994, 2011.

Zhao, A.D., Stevenson, D.S. and Bollasina, M.A., The role of anthropogenic aerosols in future precipitation extremes over the Asian Monsoon Region, Climate Dynamics 52:6257-6278, doi: 10.1007/s00382-018-4514-7, 2019

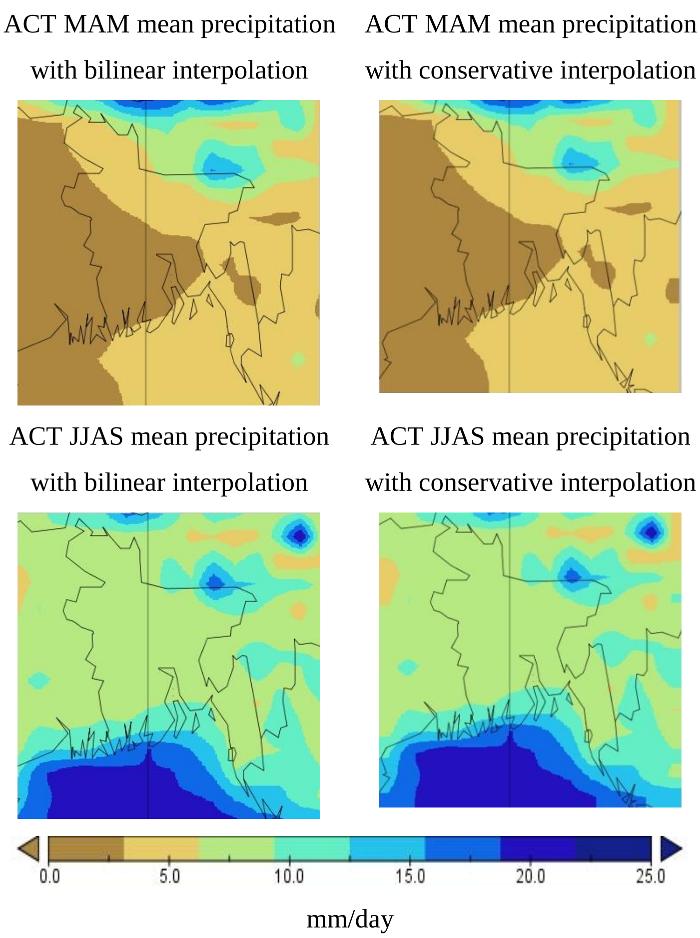

Figure AC2.a: Comparison between two interpolation methods applied for seasonal mean precipitation during JJAS and MAM over Bangladesh.

Old figure | Updated figure

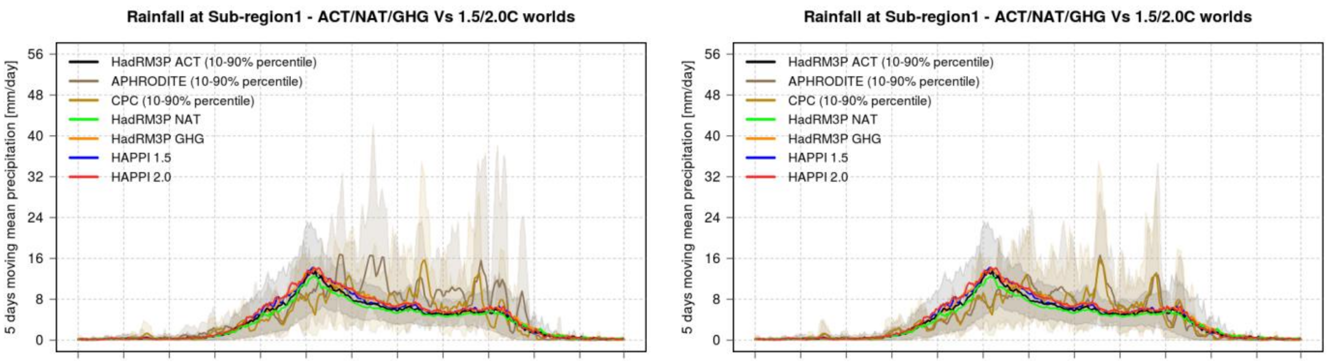

Figure AC2.b: Comparison between old and updated versions of annual cycles of 5-day precipitation over the four sub-regions of Bangladesh.

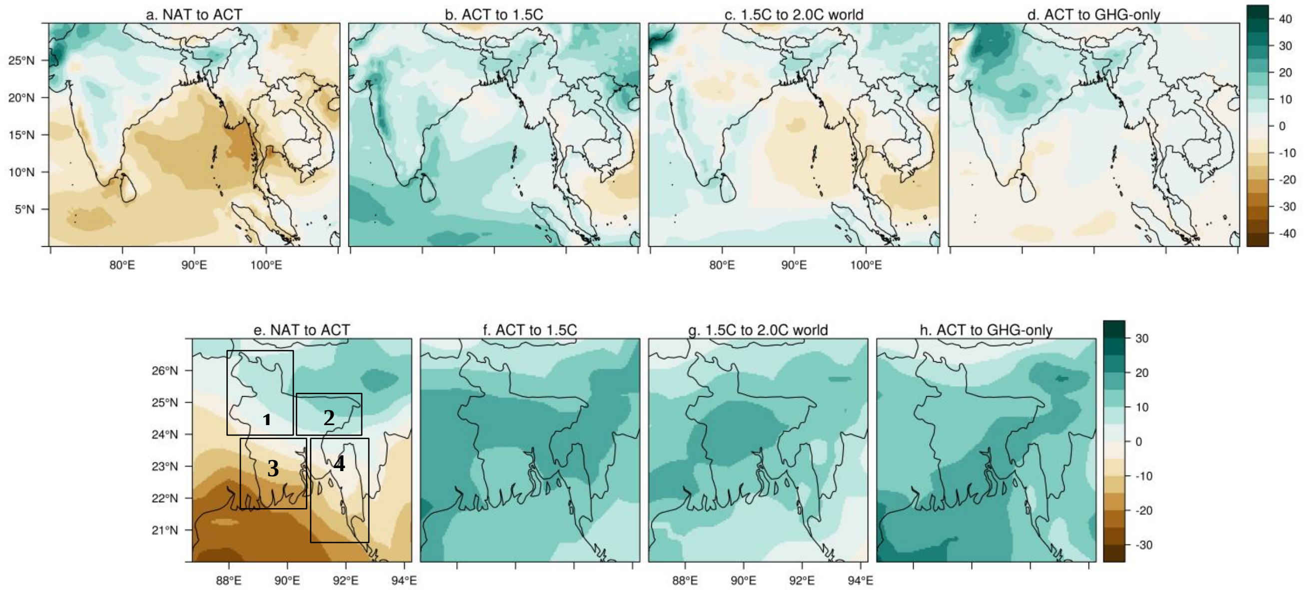

Figure AC2.c: Percentage change (PC) in the MAM seasonal mean rainfall between different forcing scenarios. The top row (panels a-d) shows the regional PC over central parts of the South Asia. a. ACT rainfall PC relative to NAT b. ACT rainfall PC relative to HAPPI 1.5°C c. HAPPI 1.5°C rainfall PC relative to HAPPI 2.0°C d. ACT rainfall PC relative to GHG-only. Bottom row (panels e-h) shows the PC in the same way but over Bangladesh. The four boxes (1-4) on top of the panel e represent the four sub-regions of Bangladesh.

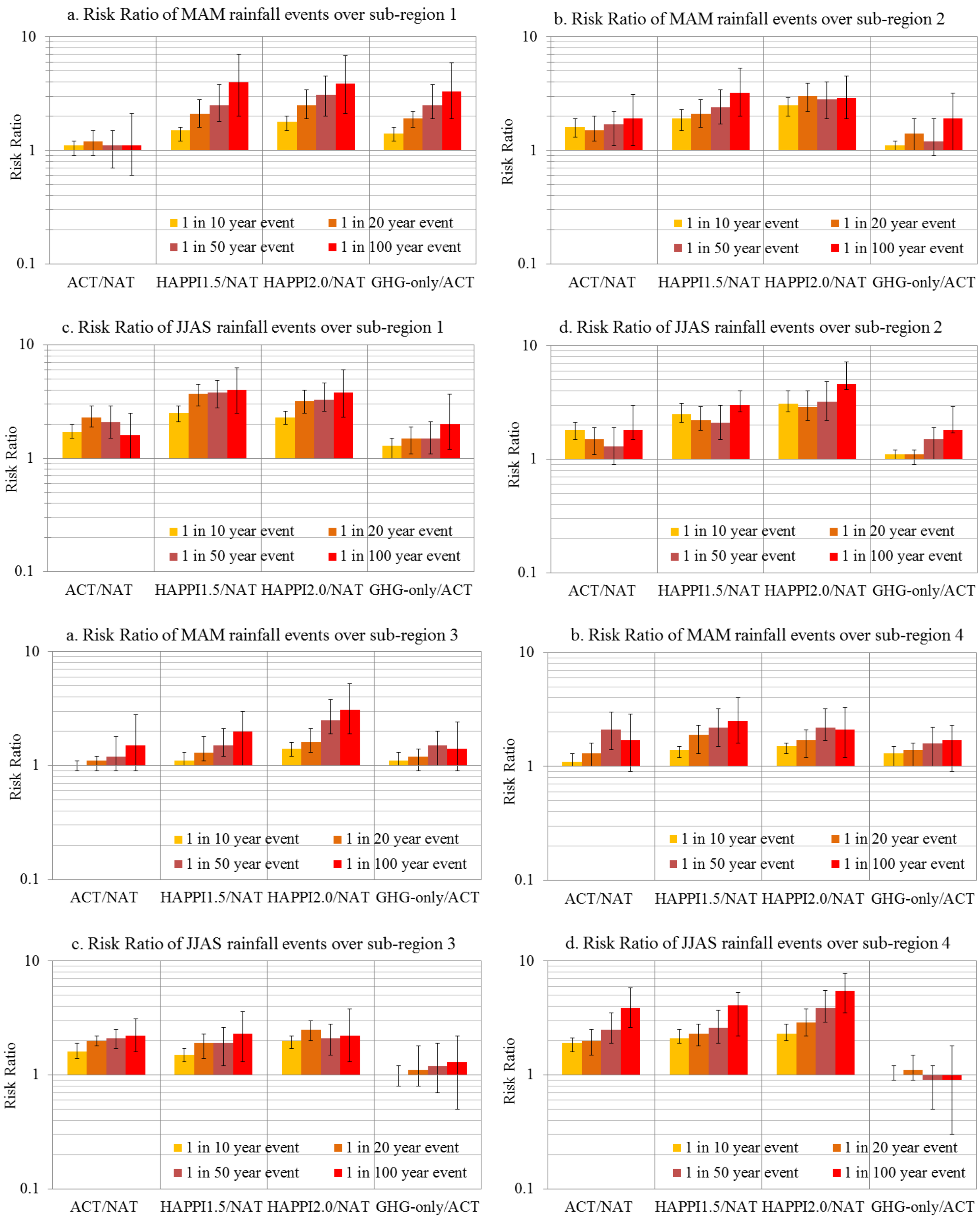

Figure AC2.c: The risk ratios of four specific rainfall events with return periods of 10, 20, 50, and 100 years between ACT/NAT, HAPPI 1.5/NAT, HAPPI 2.0/NAT and GHG-only /ACT over the two northern sub-regions 1 and 2 during MAM (top two panels of a. & b.) and JJAS (bottom two panels of c. & d.). The error bars indicate the associated uncertainty range with 95% confidence level for individual event. Same as Figure AC2.c but for MAM and JJAS risk ratios over the two southern sub-regions 3 and 4.

This study focuses on the investigation of changes in total and extreme precipitation in Bangladesh due to changes in greenhouse gas and aerosol concentrations. Large ensembles of regional climate simulations are used to represent regional dynamics and aerosol effects with sufficient detail and at the same time obtain statistical robust results also for extreme events with long return periods. In my opinion, the research resented in this manuscript is generally sound and provides novel insights (although not outstandingly new/innovative) into future rainfall changes in a highly impact-relevant region. However, I think the presentation and discussion of the research needs a substantial revision before the manuscript could be published. In my view, the interpretation of the results is too superficial at several places throughout the manuscript. Furthermore, the language and wording are not always adequate. With respect to the second point, I list a few issues below, but this list is not complete, and actually the native speakers among the co-authors should be able to fix this in a better way than I am.

We thank for the constructive comments from the anonymous Reviewer 3. We have carefully revised the manuscript to incorporate necessary amendments as per suggestions. Responses to the Referee Comments 3 (RC3) are presented in the following Author's Comments 3 (AC3):

RC3 Specific Comments

RC3: Page 1 Line 22: As this is a model study, I'd avoid the term "impacts were observed"

AC3: Rewritten the line as "Climate change impacts on the probabilities of extreme rainfall events are found during both pre-monsoon and monsoon seasons, but the level of impacts are spatially variable across the country." See **page 1 lines 26-27**

RC3: P 1 L 28: "specifically with respect to...": I was confused when reading this as I though the whole study would focus on extreme events. It is not clear from the abstract that also seasonal mean rainfall is analyzed.

AC3: To make it clear that we have also looked at climate change impacts on seasonal mean rainfall, we have now added the following line in abstract: "Both GHGs and anthropogenic aerosols influence changes in seasonal mean rainfall over this region." See **page 1 lines 23**

RC3: P 2 L 16: Nirapad (2017) is not in the list of references

AC3: The reference for Nirapad (2017) is now added to the Bibliography.   See **page 15 lines 13-15**

RC3: P 2 L 23: "help to provide...": wording issue

AC3: Deleted 'to provide'

RC3: P 3 L 12-14: I think these detailed information regarding the sub-regions would fit better in the methods section.

AC3: Agreed and moved to method section. See **page 5 lines 27-30**

RC3: P 3 L27: "observational" appears too often in this sentence

AC3: Rewritten as "The daily observational data sets that are used as a comparison against model results include: (i) Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE) (Yatagai et al., 2012) and (ii) NOAA's Climate Prediction Center (CPC) global 0.5° analysis (Chen et al., 2008a)." See **page 3 lines 31-33**

RC3: P 3 L 35: This is my only purely methodological comment: I am a bit sceptical with respect to the usage of bi-linear interpolation, as this does not conserve the area-average rainfall amount and also biases the extremes compared to the original grid point values. I would ask the authors to at least test the sensitivity of their approach using a more appropriate conservative interpolation method (see, e.g., Chen and Knutson, 2008, doi:10.1175/2007JCLI1494.1).

AC3: Thank you for the comment. We have checked our ACT precipitation data over Bangladesh in this regard. As per figure AC2.a, we can argue that changing the method from bilinear interpolation to conservative have no effect on the high intensity precipitation events.

RC3: P 4: The fact that some experiments are mentioned twice (in the first paragraph and further below) leads to some repetitions.

AC3: We have now aimed at avoiding repetitions in the manuscript as good as possible.

RC3: P 4 L 16: I'd mention already here in which way the ensemble members differ from each other.

AC3: The model ensemble members differ in their initial conditions. They are either slightly perturbed, or the atmospheric field to restart the next model run is slightly different (i.e. it originates from a different member that has been run earlier). In contrast to the scenarios, all forcing parameters are the same. As far as NAT, GHG-only and the HAPPI scenarios are concerned, we use 11 different delta SST pattern (prescribed SSTs to define the lower boundary conditions). Those 11 patterns correspond to the same forcing scenario in CMIP5 (where the delta SSTs are derived from), but they do show slightly different spatial SST anomalies and add therefore additional variability to the weather@home ensemble of the counterfactual and future model scenarios.

RC3: P 4 L 33-34: This notation is awkward. I'd either write this in text form or as a "real" equation, but not mix these things up.

AC3: Agreed, we have now removed the equations and only kept text to describe this model ensemble.

RC3: P L 12-15: This description of the aerosol affect is too short and not very clear. The term "omitted aerosol induced rainfall" should be explained. I am also confused by the sign of the signal and the figure caption: The caption of Fig. 2 says that the figure shows present-day relative to GHG only; positive values would thus mean that the present-day rainfall including the aerosol effect is larger than the rainfall due to GHG only, which is not consistent. Finally, before directly linking this result to potential future decreases in the aerosol effect already in the second sentence, the actual content of the figures should be described and explained.

AC3: The positive values for percent change in MAM mean rainfall shown in Fig. 2d in present-day ACT relative to GHG-only indicates the additional rainfall that could happen in the present-day if only GHGs were the dominant forcing and if anthropogenic aerosols (reduced to pre-industrial levels) were not effecting rainfall. But, instead of such additional rainfall, we see a drying effect in present-day ACT relative to NAT because existing aerosols over-compensate the GHG warming effects over this region.

RC3: P 6 L 19-28: I think this whole discussion is too superficial. There are many speculations on how thermodynamic and dynamic effects could influence the precipitation changes which, in my view, are speculative and should be based on a more quantitative and solid analysis. For instance, I am not sure how an "approximately linear" scaling is deduced from the data presented in this study. If this just refers to the differences between the 1.5 and 2.0 simulations, I could well imagine a case in which precipitation increases due to both increase in the atmospheric moisture content and in the monsoon circulation, and this increase is amplified in the 2.0 case, which may also produce a linear change over these simulations. Moreover, is a linear scaling really what we expect thermodynamically? The Clausius-Clapeyron relation is non-linear.

AC3: We are indeed speculating based on work by others (e.g. Bollasina et al. 2011). It is beyond the scope of this paper to investigate the dynamic response in detail. We are planning on doing that in a more advanced study with additional model simulations from HAPPI, but for now all we do is to "indicate" or "suggest" that a combination of mechanisms might be at play. None of what we say is conclusive, but it provides a potential explanation as to which factors could be at play. We can simply delete this paragraph, yet we believe that this would severely affect the integrity/content of this section. We would therefore pledge to keep the gist of the paragraph. We have added a sentence clarifying that our statements are rather speculative. See **page 8 lines 9-10**.

RC3: The conclusion that dynamic changes play a secondary role should be manifested in a quantitative way. Also the statement that the thermodynamic response "usually scales with 20-40% of Clausius Clapeyron" is vague and, as such, not comprehensible.

AC3: We did reformulate in order to make a less strong conjecture as to what could be going on. We deleted the last statement (although we are not sure why it is not comprehensible).

RC3: P 7 L 1-2: I cannot follow here: In the region with the strongest decrease in Fig. 3a, the aerosol effect is small.

AC3: This sentence is now deleted to avoid confusion.

RC3: P 7 L6: The abbreviation "SPI" has not been introduced.

AC3: Added now. See **page 8 line 34-35**

RC3: P 7 L 11-3: Again I cannot follow. For instance, the changes in 5b,d are similar to those in 4b,d

AC3: This is rewritten as: "Changes in mean absolute rainfall are much more pronounced over sub-regions 1 and 2, where both MAM and JJAS rainfall exhibit clear shifts from one forcing to another forcing scenario (Fig. 4). On the other hand, over sub-regions 3 and 4, only JJAS rainfall exhibited a robust shift (Fig. 5 b & d)." See **page 8 line 40-42**

RC3: P 7 L 14: It is difficult to assess the relative change at this point, as the figures show absolute values

AC3: Not sure we can exactly follow their point. Fig. 2 and 3 (as well as S1 and S2 for SPI) show relative percent changes. We now discuss absolute changes. Can the referee elaborate on what is meant with that comment? We would highly appreciate that.

RC3: P 7 L 16-17: This doesn't fit with the interpretation in the figure caption. In general, I find it difficult to shift parts of the discussion to the figure captions.

AC3: Figure caption amended as "…… aerosol impacts over both sub-regions 1 and 2 are larger in MAM dry season than that in JJAS wet season." Part of the figure caption is now also discussed here (as opposed to the figure caption).

RC3: P 7 L 18: lapse rate and stability changes are not different feedbacks

AC3: We agree. Instead we have clarified the point and added effects on boundary layer turbulence. Rewritten as: "Consequently, direct and indirect aerosol effects, accompanied by feedbacks such as reduced lapse rate, reduced boundary layer turbulence, or a modified land-sea circulation, remain to be a potent driver for changing monsoonal rainfall amounts." See **page 9 line 4-6**

RC3: P 7 L 21: Again I don't understand what "linear" increase means here.

AC3: By linear response, we meant steady and gradual increase in the climate change impact on rainfall from one forcing scenario to another due the warming effects, for example, from ACT to HAPPI 1.5 and HAPPI 1.5 to HAPPI 2.0. In other words, a 'linear' response is when we impacts (e.g. drying, wettening, warming, cooling) continue as a function of increased warming, i.e. scaling with global mean surface temperature. We have now added a line to explain this in the revised manuscript as: "By linear response, we meant steady and gradual increase in the climate change impact on rainfall from one forcing scenario to another due the warming effects starting from NAT to ACT, ACT to HAPPI 1.5 and HAPPI 1.5 to HAPPI 2.0." **See page 8 lines 7-9**

RC3: Section 3.3, first paragraph: There is an imbalance between the amount of text/discussion and the number of figures. The reader is left alone with much of the material shown in Figs. 6-9. Either expand this discussion, or, if you think that the results are not that important, move parts of the figures to the supplement.

AC3: This section is expanded to discuss results from figures 6-9.

RC3: P 8 L 4: "appear to counter": I cannot see how you come to this conclusion.

AC3: Rephrased: "Might partially" instead of "appear". See **page 9 lines 40**

RC3: P 8 L 24: "to a lesser extent": Really? Aren't the relative changes larger for the extremes?

AC3: Revised to: [are projected to increase seasonal mean and extreme rainfall probabilities during] "probabilities". See **page 10 lines 17-18**

RC3: P 8 L 31: "we conclude that the drier subregions ...": I don't think this has been demonstrated. To show this, the masking effect has to be quantified. Furthermore, it is not clear to me which region and season you're referring to.

AC3: This part was indeed very confusing. Please accept our apologies. We have revised this paragraph including a more quantitative statement. See **page 10 lines 25-30**

RC3 Comments on Figures

*RC3: **Fig. 1**: I think this figure is too busy. I cannot distinguish the different shadings and also the lines of the observations are hard to see.*

AC3: Figure 1 is redone with higher resolution and better visual clarity (see below).

*RC3: **Fig. 3**: shorten caption (as Fig. 2, but for the monsoon season)*

AC3: All figure captions are now reasonably shortened.

*RC3: **Fig. 4**: I cannot follow the interpretation in the caption. For instance, I don't see such large differences in the masking effect between the regions. More in general, it is hard for me to understand how the masking effect is quantified here.*

AC3: You are right; the masking effects vary only with wet and dry seasons. The figure interpretation is rewritten as: “The figure shows that aerosol impacts over both sub-regions 1 and 2 are larger in MAM dry season than that in JJAS wet season.” We compare the NAT, ACT and GHG-only (green, gray and orange boxplots) results to quantify the aerosol masking effects for both sub-regions.

*RC3: **Fig. 10**: Again, the interpretation in the caption is unclear (e.g., which region and season are you referring to?)*

AC3: Rewritten the figure caption as follows: Figure AC3.d: Same as Figure AC3.c but for sub-region 3 and 4. During MAM over both sub-regions 3 and 4, aerosol effects suppress the mean rainfall change between NAT and ACT (i.e., ACT rainfall is lower than NAT). On the other hand, during JJAS over both sub-regions 3 and 4, with lesser aerosol masking effects, ACT has higher mean rainfall than NAT and GHG-only would have noticeably much higher mean rainfall.

References:

Bollasina, M.A., Ming, Y. and Ramaswamy, V.: Anthropogenic Aerosols and the Weakening of the South Asian Summer Monsoon, Science 334 (6055), 502-505, doi: 10.1126/science.1204994, 2011.

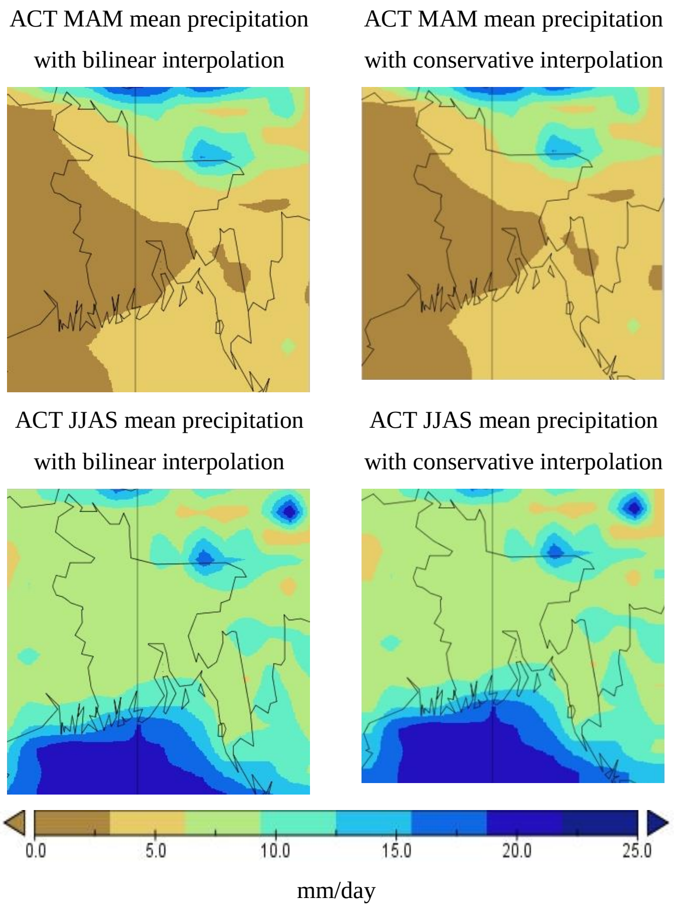

Figure AC3.a: Comparison between two interpolation methods applied for seasonal mean precipitation during JJAS and MAM over Bangladesh.

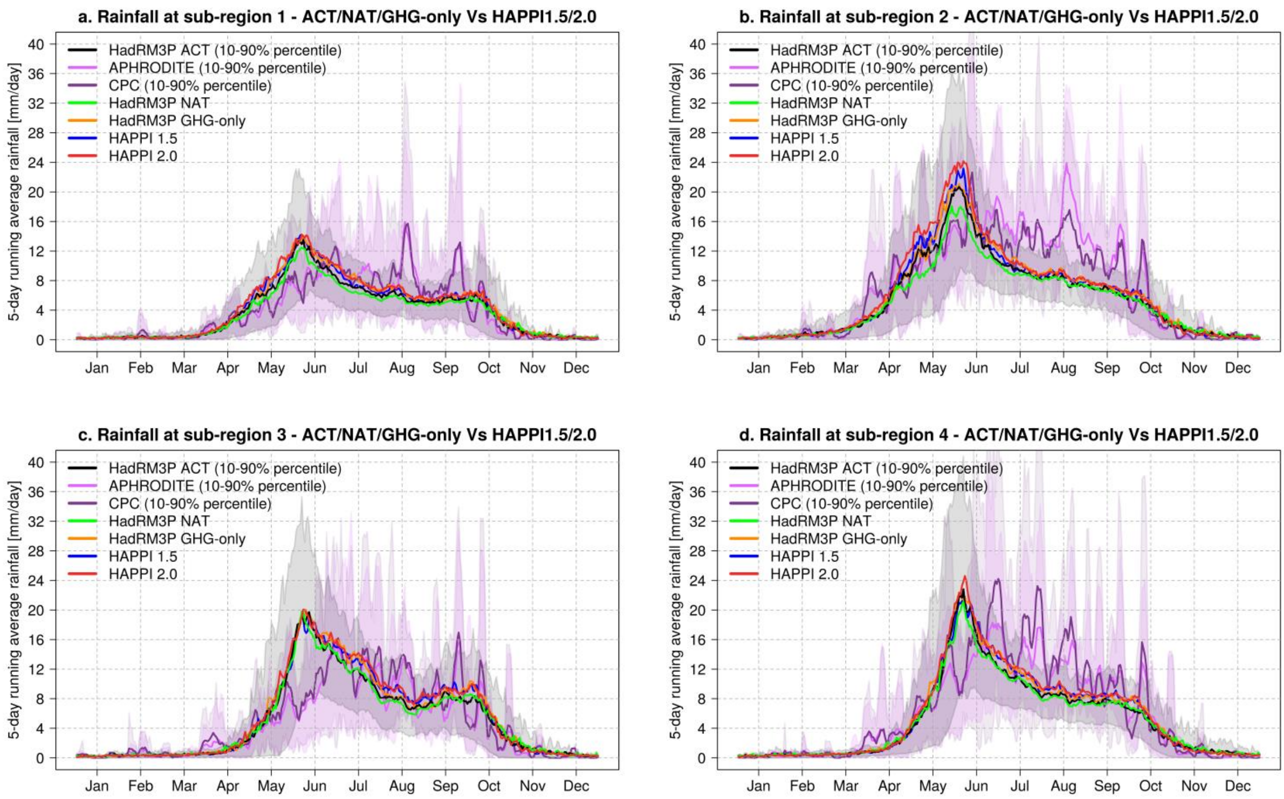

Figure AC3.b: Seasonal cycles of five day mean rainfall under different forcing scenarios over the four sub-regions of Bangladesh. The ACT (black), NAT (green) and GHG-only (orange), HAPPI 1.5 (blue) and 2.0 (red) ensembles are compared with the observations from APHRODITE (light purple) and CPC (dark purple). The model adequately captures the seasonal cycle of rainfall compared to observation but underestimates monsoon (JJAS) rainfall. Only over sub-region 2, rainfall is clearly shifting from NAT to ACT, from ACT to GHG-only, from ACT to HAPPI 1.5 and from HAPPI 1.5 to 2.0 forcing scenarios.

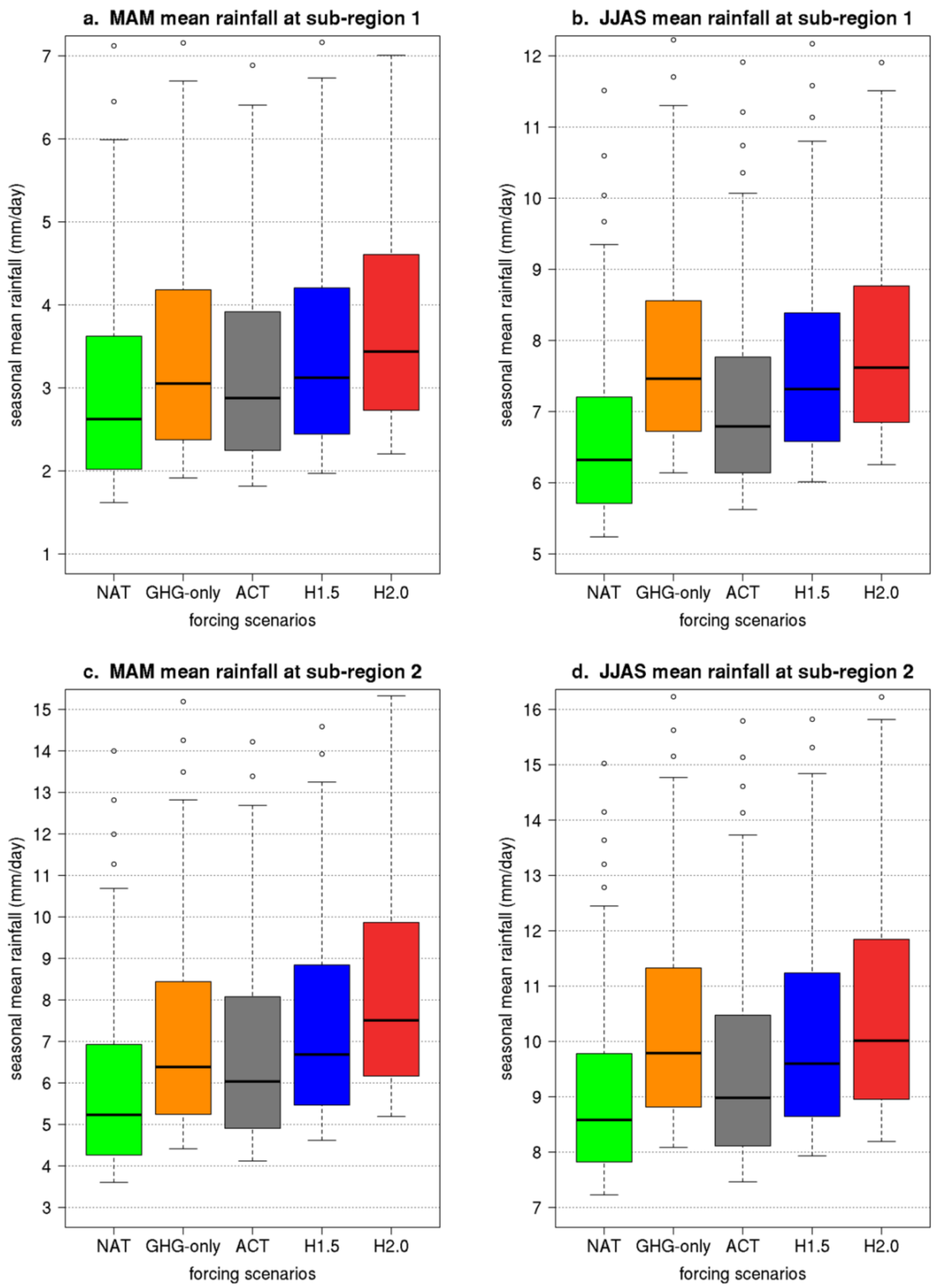

Figure AC3.c: Seasonal mean rainfall in MAM (left column) and JJAS (right column) over the sub-regions 1 and 2 (top and bottom row) of Bangladesh. Green, orange, grey, blue and red colours represent NAT, GHG-only, ACT, HAPPI 1.5 and HAPPI 2.0 ensembles respectively. Each panel has different y-scale range to clearly indicate the details of changes in the median values between different model ensembles. The horizontal black line in each box indicates the median value, the bottom and top limits of the box represents the 25th and 75th percentiles respectively. The figure shows that aerosol impacts over both sub-regions 1 and 2 are larger in MAM dry season than that in JJAS wet season.

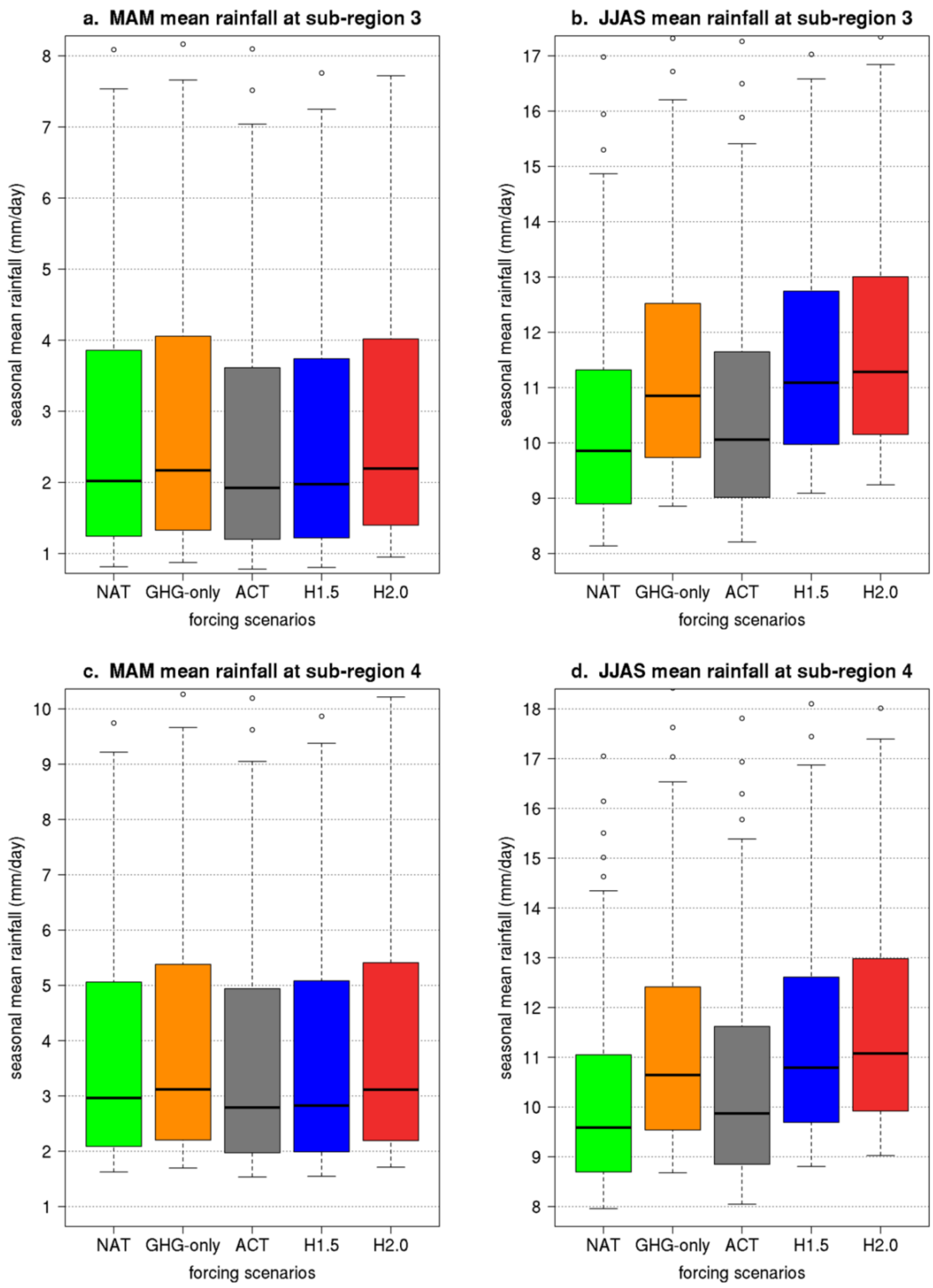

Figure AC3.d: Same as Figure AC3.c but for sub-region 3 and 4. During MAM over both sub-regions 3 and 4, aerosol effects suppress the mean rainfall change between NAT and ACT (i.e., ACT rainfall is lower than NAT). On the other hand, during JJAS over both sub-regions 3 and 4, with lesser aerosol masking effects, ACT has higher mean rainfall than NAT and GHG-only would have noticeably much higher mean rainfall.

#marked up version of manuscript

Risks of seasonal extreme rainfall events in Bangladesh under 1.5 and 2.0 degrees' warmer worlds – How anthropogenic aerosols change the story

Ruksana H. Rimi[1], Karsten Haustein[1], Emily J. Barbour[1,2], Sarah N. Sparrow[3], Sihan Li[1,3], David C.H. Wallom[3], and Myles R. Allen[1].

[1]Environmental Change Institute, School of Geography and the Environment, University of Oxford, Oxford, OX1 3QY, UK.

[2] Commonwealth Scientific and Industrial Research Organisation, Land and Water, Canberra, ACT 2601, Australia.

[3]Oxford e-Research Centre, Department of Engineering Science, University of Oxford, Oxford, OX1 3QG, UK.

Correspondence to: Ruksana H. Rimi (ruksana.rimi@ouce.ox.ac.uk)

Abstract. Anthropogenic climate change is likely to increase ~~the frequency~~ 'risk' (probability of occurrence of a hazard) of extreme weather events in the future. Previous studies have robustly shown how and where climate change has already changed the risks of weather extremes. However, developing countries have been somewhat underrepresented in these studies, despite high vulnerability and limited capacities to adapt. How additional global warming would affect the future risks of extreme rainfall events in Bangladesh needs to be addressed to limit adverse impacts. Our study focuses on understanding and quantifying the relative risks of extreme rainfall events in Bangladesh under the Paris Agreement temperature goals of 1.5°C and 2°C warming above pre-industrial levels. In particular, we investigate the influence of anthropogenic aerosols on these risks given their likely future reduction and resulting amplification of global warming. Using large ensemble regional climate model simulations from weather@home under different forcing scenarios, we compare the risks of rainfall events under pre-industrial (natural), current (actual), 1.5°C, and 2.0°C warmer and greenhouse gas (GHG)-only (with pre-industrial levels of anthropogenic aerosols ~~removed~~) conditions. Both GHGs and anthropogenic aerosols influence changes in seasonal mean rainfall over this region. For extreme rainfall events, we find that the risk of a 1 in 100 year rainfall event has already increased significantly compared with pre-industrial levels across parts of Bangladesh, with additional increases likely for 1.5 and 2.0 degree warming (of up to 5.5 times higher, with an uncertainty range of 3.5 to 7.8 times). Climate change impacts on the probabilities of extreme rainfall events ~~were observed~~ are found during both pre-monsoon and monsoon seasons, ~~periods~~ but ~~were~~ the level of impacts are spatially variable across the country. ~~in terms of the level of impact.~~ Results also show that reduction in anthropogenic aerosols plays an important role in determining the overall future climate change impacts; by exacerbating the effects of GHG induced global warming and thereby increasing the rainfall intensity. We highlight that the net aerosol effect varies from region to region within Bangladesh, which leads to different outcomes of aerosol reduction on extreme rainfall statistics, and must therefore be considered in future risk assessments. Whilst there is a substantial reduction in the impacts resulting from 1.5°C compared with 2°C warming, the difference is spatially and temporally variable, specifically with respect to seasonal extreme rainfall events.

1 Introduction

One of the major goals of the ~~The~~ 2015 Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC), on "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C" (UNFCCC, 2015), needs strong support from research on the nature, benefits and feasibility of this challenging goal. This Agreement calls for the quantification and comparison between the impacts of 1.5°C versus 2.0°C warmer global temperatures on different climate related aspects such as extreme weather events.

While assessing both risks and vulnerabilities to incremental increases in global mean temperature, the discrimination of the impacts of different radiative forcing contributions as well as the quantification of spatially varying changes in risk are crucially important. For example, highly unusual heat extremes that are virtually absent in the present climate in South Asia, would affect around 15% of land area of this region under 1.5°C and around 20% of land area under 2°C warming (The World Bank, 2012). The increase in heavy monsoon rainfall intensity for South Asia is projected to be 7% under 1.5°C and 10% under 2°C warming compared to pre-industrial conditions (Schleussner et al., 2016). Populations of this region largely depend on the stability of the monsoon, which provides water resources for agricultural production (The World Bank, 2012). It is projected that the years with above-normal monsoon rainfall will be more frequent (Endo et al., 2013; Kripalani et al., 2007). The seasonality of rainfall will be amplified with more rainfall during the wet season (Fung et al., 2011; Turner and Annamalai, 2012). The number of extreme rainfall events are projected to increase as well (Endo et al., 2012; Kumar et al., 2011 in Vinke et al., 2017). As a consequence of additional global warming, parts of East Asia and India are likely to have more frequent daily extreme rainfall events in monsoon season (Chevuturi et al., 2018). Here we assess whether these generalized projections are also valid using a large ensemble regional climate model framework focusing on Bangladesh.

Bangladesh is potentially a hotspot of climate change impacts as it is vulnerable to a combination of increasing challenges from record-breaking temperatures, extreme rainfall events, more intense river floods, tropical cyclones, and rising sea levels (The World Bank, 2012). Bangladesh has a tropical monsoon climate, flat and low-lying topography, and unique geographical location in the Ganges-Brahmaputra-Meghna Basin (Banglapedia, 2012; Rawlani and Sovacool, 2011). For these features, heavy rainfall events in the pre-monsoon (during Mar-Apr-May; MAM) and monsoon (during Jun-Jul-Aug-Sep; JJA) seasons are associated with a high risk of flooding and landslides almost every year. ~~In recent years, the frequency of high-intensity rainfall events has shown an increasing trend in the observations.~~ The frequencies of observed high-intensity rainfall events are increasing in the recent years (Murshed et al., 2011). For example, in 2017, heavy rainfall across the upstream Meghalaya hills in India and in Bangladesh caused pre-monsoon floods in March in the northeastern parts of the country. Consequently, vast areas of Haors (local name for lowland wetlands) and low-lying areas were inundated and most of the nearly-harvestable 'Boro' paddy crop (a local high yielding variety of paddy) was damaged (Nirapad, 2017). In June 2017, ~~heavy rain induced floods and landslides killed at least 156 people.~~ at southeastern parts of Bangladesh heavy rainfall caused devastating floods and multiple landslides killing at least 156 people (Paul and Hussain, 2017). National Aeronautics and Space Administration (NASA)'s near-real time Integrated Multi-satellitE Retrievals for Global Precipitation Measurement, GPM (IMERG) data estimated the heaviest rainfall accumulation of more than 510 mm in only 3 days (12-14 June 2017) ~~in southeastern Bangladesh~~ (Gutro, 2017).

Considering the unfolding change in risk of heavy rain in the region under present-day conditions how would a 1.5°C and a 2.0°C warmer world change the probability of extreme rainfall events in Bangladesh? If climate change is already playing a role, then similar events are likely to occur even more frequently as global warming continues in the future (Faust, 2017). Reliable information regarding the relative changes in future risks of extreme rainfall events can help ~~to provide~~ local decision makers to address the problem, develop appropriate adaptation strategies and allocate resources to minimize loss and damage associated with potential climate extremes. ~~A multi global climate model (GCM) ensemble based study conducted for northwestern part of Bangladesh reported ~9% and ~18% increase in mean seasonal rainfall during pre-monsoon (Mar-May) and monsoon (Jun-Sep) seasons respectively by 2090~~ According to global climate model (GCM) ensemble based study, by 2090, the north-western part of Bangladesh would experience ~9% and ~18% increase in the pre-monsoon and monsoon mean rainfall respectively (Kumar et al., 2014). Caesar et al., (2015) used the high resolution (25 km) regional climate model (RCM), HadRM3P that is nested in the global HadCM3 model and projected a large increase in the very heavy daily rainfall events (>99th percentile, i.e., >23.8mm/day) and a decrease in the light-moderate rainfall events (<75th percentile, i.e., <12.3mm/day) during monsoon season (Jun-Sep) over Bangladesh by 2099. According to PRECIS (Providing REgional Climates for Impact Studies) model projection for 2080, the north-eastern ~~parts of~~ Bangladesh would experience 0.42–75% more pre-monsoon rainfall compared to the baseline of 1971–2000 (Nowreen et al., 2015). While previous studies projected future changes in the seasonal mean or extreme rainfall events over a specific part or whole Bangladesh; none had the benefit of using very large model ensembles of high resolution ~~regional climate model~~ RCM to examine exceptionally rare extreme rainfall events (e.g., events with 100-1000 year of return periods); explained whether or not anthropogenic climate change played a role in changing the probabilities of those projected future rainfall events; and explored how anthropogenic aerosols changed the overall climate change impacts on rainfall events. The Fifth Phase Coupled Model Inter-comparison Project (CMIP5) models produced a broad range of temperature projections as a function of model sensitivity (van Vuuren et al., 2011). ~~However, the specified warming targets set in the Paris Agreement were not addressed in those experiments.~~ CMIP-style experiments are not ideal to provide with impact assessments specifically at 1.5°C or 2°C warming, because in these experiments, uncertainty increases with time and is dominated by responses and variability. While the UNFCCC in particular asking about the comparative risks associated with 1.5°C and 2°C warming, irrespective of what emission path is followed to achieve it. ~~Hence~~ The Half a degree Additional warming, Prognosis and Projected Impacts (HAPPI) framework has been developed to address this call and provide with impact assessments specifically targeted for 1.5°C and 2.0°C warming (Mitchell et al., 2016, 2017). There are only a few studies using CMIP5 (e.g., Fahad et al., 2017), or PRECIS (e.g., Nowreen et al., 2015) ~~runs~~ simulations that investigated future changes in ~~the~~ rainfall events over Bangladesh, but none of these have specifically addressed the warming targets of the Paris Agreement. The novelty of this study lies in meeting all these aforementioned challenges.

We considered anthropogenic aerosols in addition to greenhouse gases (GHGs) as a potential contributing factor in changing the risks of extreme rainfall events. Because aerosols can influence regional climate and change the risks of rainfall events by radiative forcing ~~and microphysical effects~~ (Guo et al., 2013; Li et al., 2016). Furthermore, extreme rainfall events have higher sensitivity to aerosols removals, per degree of surface warming, in particular over the major aerosol emission regions like Asia (Samset et al., 2018). Therefore it is important to explore aerosol impacts while assessing the changes in the risks of extreme rainfall events under additional global warming scenarios of 1.5 and 2.0 degrees' of Paris Agreement.

Drawing on the large ensemble of regional climate model (RCM) runs generated with the weather@home system (Guillod et al., 2017; Massey et al., 2015) within the HAPPI experimental framework, ~~here~~ we quantify changing rainfall risks for Bangladesh during MAM and JJAS ~~pre-monsoon (Mar-May; MAM) and monsoon (Jun-Sep; JJAS) seasons. In order to look at local sub-regional scale rainfall risks within Bangladesh, we use sub-regions 1-4 located at north-west (88°-90°E, 24°-26°N), north-east (90.5°-92.5°E, 24°-25.5°N), south-west (89°-91°E, 21.5°-23.5°N) and south-east (91°-93°E, 20.5°-24°N) respectively.~~ The risk of extreme rainfall events is evaluated for a counterfactual 'natural', current 'actual' and future 1.5 and 2.0 degrees warmer climate scenarios, ~~a counterfactual 'natural' scenario as well as~~ a ~~current climate with no anthropogenic aerosols (GHG-only) scenario~~. In particular, ~~the~~ The impact of anthropogenic aerosol emissions is quantified and discussed based on the GHG-only scenario.

We first introduce data and methods in Section 2, whilst a summary of model performance is presented in Section 3.1. ~~2.2. Further details on model evaluation are provided in Rimi et al. (under review).~~ We then assess percentage changes and standardized changes in the seasonal mean rainfall within five forcing scenarios (Natural, Actual, 1.5°C, 2.0°C and GHG-only) in Section 3.2. Finally, in Section 3.3 we ~~explore~~ detect the relative shifts in the probabilities of MAM and JJAS daily (and 5-day) rainfall extremes ~~during the pre-monsoon and monsoon seasons using return times over the four sub-regions, and identify the relative shifts in the probabilities of extreme rainfall events~~ between the different forcing scenarios. The results are discussed in context of regional vulnerabilities and observed changes in Section 4.

2 Data and Methods

2.1 Observational data

~~Two~~ The daily observational ~~dataset~~ data sets that are used as a comparison against model results include:~~, observational~~ (i) Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE) ~~daily rainfall data for the duration of 2006-2015~~ (Yatagai et al., 2012) and (ii) NOAA's Climate Prediction Center (CPC) global 0.5° analysis ~~of daily rain gauge measurements covering 2006-2015~~ (Chen et al., 2008a). APHRODITE is a ~~the only long-term continental-scale, daily gridded rainfall dataset (available for 1951-2007) with high-resolution grids for Asia;~~ high-resolution daily gridded rainfall dataset for Asia (V1901, available for 1998-2015); created primarily with data obtained from a rain-gauge-observation network. CPC global daily rainfall dataset (available from 1979 to present) is constructed through a unified analysis of gauge-based daily rainfall over global land (Chen et al., 2008b). Basic facts about these two observational data sets are presented in ~~the~~ Table S1 in the supplementary information. ~~APHRODITE and CPC were also used in the model evaluation conducted by Rimi et al., (2019).~~ Both model and observation data is re-gridded using bi-linear interpolation method to have similar and comparable grid structures.

2.2 Model setup and experimental design

The weather@home is part of the climateprediction.net programme (Stainforth et al., 2005) ~~programme~~ and is able to generate very large ensembles of climate model simulations by harnessing spare CPU time on a network of volunteers' personal computers (Allen, 1999; Stott et al., 2004; Massey et al., 2015; Otto, 2017). For this study, we use the high resolution (50 km) RCM, ~~of~~ HadRM3P (over South Asia region) that is nested in the global atmosphere-only HadAM3P model of weather@home system and is driven by prescribed sea surface temperatures (SSTs) and radiative forcing (Massey et al. 2015; Guillod et al. 2017) to generate the required model ensembles with initial condition perturbations. The model includes a sulphur cycle (Jones et al., 2001) and uses the updated Met Office Surface Exchange Scheme version 2 (MOSES2; Essery et al., 2003). Recent ECLIPSE v5a global emissions dataset (Klimont et al., 2013) is used to prescribe the sulphur dioxide fields in the model. Information about the procedure of using this data in the model is given the supplementary material.

~~of present-day actual climate conditions (denoted as 'ACT'); the counterfactual world with natural climate conditions of pre-industrial period with no anthropogenic warming influences (denoted as 'NAT'); and the hypothetical world with the GHG-only climate condition where the anthropogenic aerosols are reduced to pre-industrial levels (denoted as 'GHG-only'). Evaluation of the model for the region was conducted by Rimi et al (Rimi et al., 2019a), and demonstrated a reasonable agreement between model results and observational datasets for extreme rainfall events. The model is therefore considered fit for purpose in evaluating the potential impacts of climate change.~~

HAPPI experiments are designed to address ~~the~~ research questions relating to 1.5°C and 2.0°C warming and as part of the experiments weather@home system is used to generate large model ensembles (Massey et al., 2015; Otto, 2017; Stainforth et al., 2005). Following the experimental set up of the HAPPI framework (for details see Mitchell et al., 2017), this study uses experiments of three decadal model ensembles:

1. Actual climate (denoted as 'ACT') ~~ACT~~ model ensemble with 98 members per year representing the current decade (2006–2015) with ~~the actual climatic conditions, using~~ observed SST data from the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) dataset (Donlon et al., 2012; Stark et al., 2007) and present-day atmospheric GHG and aerosol concentration.
2. HAPPI 1.5 model ensemble (2091–2100) with 98 members per year representing 1.5°C warmer than pre-industrial (1861–1880) climatic conditions, and

3. HAPPI 2.0 model ensemble (2091–2100) with 98 members per year representing 2.0°C warmer than pre-industrial (1861–1880) climatic conditions.

For the HAPPI 1.5 model ensemble, the RCP 2.6 scenario is used to provide the model boundary conditions. In RCP 2.6 scenario, the mean global temperature reaches to ~1.55°C by 2100 (Mitchell et al., 2017). Since there is no analogous CMIP5 simulation available which results in ~2°C warmer temperatures relative to preindustrial levels, a weighted combination of RCP2.6 and RCP 4.5 is used to provide the model boundary conditions of SST and sea ice for the HAPPI 2.0 model ensemble. The global mean temperature response reaches to ~2.05°C by the end of century in the HAPPI 2.0 model ensemble (Mitchell et al., 2017). Following the RCP2.6 protocol, anthropogenic aerosol concentrations are approximately ~~1/3th~~ one-third of the current levels (IPCC, 2013) in both HAPPI scenarios.

In addition, we use two model ensembles of hypothetical ~~world~~ climate conditions:

4. Natural (‘NAT’) ~~NAT~~ model ensemble with 98 members per year representing the current decade (2006–2015) climatic conditions, but here the modelled SST patterns of anthropogenic forcing (ΔSSTs ~~hereinafter~~) are removed from the OSTIA observed SSTs to simulate a counterfactual world. ΔSSTs are generated from the CMIP5 archive.

   ~~**Anthropogenic forcing/signals, ΔSSTs = CMIP5 Historical SSTs – CMIP5 Natural SSTs……(i)**~~

   ~~**Counterfactual World’s SSTs = OSTIA Observed SSTs - ΔSSTs……………………………(ii)**~~

   In this case, HistoricalNat simulations are subtracted from the Historical simulations as described in Schaller et al. (2016), thereby generating a representation of human influences on the SSTs that can be removed from the OSTIA SSTs. GHG and aerosol concentrations are set to pre-industrial levels.

5. ‘GHG-only’ model ensemble with 98 members per year representing the current decade (2006–2015) climatic conditions, but with anthropogenic aerosol concentrations reduced to pre-industrial levels to simulate a hypothetical climate, where impacts of aerosols are removed. The difference between ACT and GHG-only conditions simulates the net aerosol effect under current conditions assuming additive behaviour of different radiative ~~forces~~ forcing. The GHG-only model ensemble with anthropogenic aerosols reduction scenario in the HadRM3P model is satisfactorily representative when compared with the other GCMs (Haustein et al., in progress). Based on the very limited sample of CMIP5 aerosol only (AA) experiments, we found that the resulting ΔSST patterns are reasonably similar compared with ΔSSTs from ACT minus GHG-only (not shown).

2.3 Methods

To understand how seasonal mean rainfall changes from one climate condition to another, we looked at percent change (PC) and standardized precipitation index (SPI) change between different two forcing scenarios (from pre-industrial NAT to current ACT, ACT to HAPPI 1.5, HAPPI 1.5 to 2.0 and from ACT to GHG-only). PC and SPI analyses are done for rainfall changes over the central parts of South Asia and then over Bangladesh. For brevity, the supplementary text includes the details of the calculation methods for PC and SPI changes.

In Bangladesh, any MAM extreme rainfall events are known to cause flash floods and substantial crop damage (Ahmed et al., 2017). Bangladesh receives more than 75% of the annual total rainfall during JJAS (Shahid, 2010). An extreme rainfall event in this period can therefore cause wide-spread flooding and landslide eventually leading to loss of lives and livelihoods. A high impact post-monsoon (Oct-Nov; ON) rainfall event may be associated with the coastal floods that occur due to storm surges or tidal effects along the northern part of Bay of Bengal (Hossain, 1998).

Considering meteorological hazards and potential impacts, MAM and JJAS extreme rainfall events are analyzed in this study while, ON rainfall events are excluded. Winter (during Dec-Jan-Feb; DJF) season is also excluded because little or no rain occurs during DJF and we are interested in wet extremes.

We use sub-regions 1-4 located at north-west (88°-90°E, 24°-26°N), north-east (90.5°-92.5°E, 24°-25.5°N), south-west (89°-91°E, 21.5°-23.5°N) and south-east (91°-93°E, 20.5°-24°N) respectively. The two eastern sub-regions 2 and 4 are the rainier parts of the country compared to the other two western sub-regions of 1and 3. MAM and JJAS extreme rainfall events with up to 100 years of return periods are adequately well captured by the HadRM3P model over these same 4 sub-regions in Bangladesh when compared to high resolution gridded observation datasets (Rimi et al., 2019a). Such pre-evaluated model simulations provide confidence in analyzing comparative risks of extreme rainfall events under different forcing scenarios. The model is therefore considered to be fit for assessing climate change impacts on extreme rainfall events in Bangladesh.

In Bangladesh 1- to 10-day high impact rainfall events can trigger flooding and landslides. For example, at north-east Bangladesh (sub-region 2), more than 150 mm MAM rainfall over a 6-day period can lead to an early flash flood (Ahmed et al., 2017). In contrast, at south-east Bangladesh (sub-region 4), more than 350 mm JJAS rainfall over a 3-day period is enough to cause a landslide (Ali et al., 2014). For a wide-spread river flooding e.g., the Brahmaputra River Basin flooding in August 2017, 10-day extreme rainfall event is considered (Philip et al., 2018).

Considering such variations in rainfall magnitudes causing different hazards, we focused on daily and 5-day rainfall events to analyze the potential risks. The seasonal cycles of presented here are based on 5-day rainfall, which is used to represent the timescale responsible for river flooding as opposed to daily extremes that cause flash floods primarily in the pre-monsoon season.

"Return time" of an event, also known as the "return period" is the likelihood of an event occurring, defined by a particular variable exceeding a certain threshold during a given time interval. If variable X is equal to or greater than an event of magnitude x_T, occurs once in T years, then the probability of occurrence $P(X \geq x)$ in a given year of the variable is (Wilks, 2011):

$$P(X \geq x = \frac{1}{T}) \text{ or, } T = \frac{1}{1 - P(X \geq x_T)}$$

A "1 in 10 year event" is an event with a 10% chance of occurring. On the contrary, the rarest event is a "1 in 1000 year event", with a 0.1% chance of occurring in a given year. The rainfall amounts associated with the 50- or 100-year return periods are extracted from the 98th and 99th percentiles, respectively, of a fitted distribution (i.e., $[1–0.98^{-\text{year}}]^{-1}$ = 50 years and $[1–0.99^{-\text{year}}]^{-1}$ =100 years) (Wilks, 1993). The uncertainty of the return period is calculated using bootstrapping method. The time series of each ensemble is resampled a 1000 times using bootstrapping to derive 5 to 95% confidence intervals for return periods. We note that structural model uncertainty (such as parameter sensitivity) is not included in our uncertainty estimate.

Return time plots are used to explore the relative risks of rare events (like those with probabilities of <= 1 in 100 years). To construct the return time plots ~~of~~ for MAM and JJAS ~~the~~ daily (and ~~five~~ 5-day) ~~mean~~ rainfall events ~~in pre-monsoon and monsoon seasons~~, we use 98 plausible model realizations ~~with initial condition perturbations~~ for the 10-year period of each model ensemble ~~within 2006-2015~~. For each year, three (MAM) ~~or,~~ and four (JJAS) months of data are used for pre-monsoon and monsoon season, respectively. The model uses a 360-day calendar with all 12 months spanning for 30 days. Therefore, we have ~~90x10x98~~ 3x30x10x98 = 88,200 and 4x30x10x98 = 117,600 simulated values to calculate the return periods of ~~pre-monsoon~~ MAM and JJAS rainfall events, respectively. ~~Whereas, for the monsoon season, we have 120x10x98 = 117,600 simulated values to calculate the return periods~~. Such large sample size allows us to estimate a range of physically plausible climate conditions with focus on the tails of the distribution, which can be robustly determined. We consider all days of a season for calculating the return periods or rainfall events. In this way, we can look at low intensity rainfall events with minimum return period of 1 year, and also high intensity rainfall events with up to 98x10 = 980 years return period. However, we focused on rainfall events with high return periods that are relevant for impacts and adaptation planning (i.e., 10-100 year events).

To add a qualitative representation of the year-to-year natural variability from the ~~present-day actual climate simulated in the~~ ACT model ensemble, we use two ~~of the~~ wettest and two ~~of the~~ driest years during the decade of 2006-2015. The spatiotemporal average for the corresponding sub-region and season over the 10-year simulation period has been used to ~~determine~~ identify the two wettest and driest years. ~~; see also Table S2).~~ ACT model ensemble has the same forcings in each year for the historical period of 2006-2015; the only variability playing a role in changing rainfall intensity is therefore the natural variability of SSTs. For this reason, these two wettest and driest years of ACT model ensemble approximately indicate how much natural SST variation can contribute to changing rainfall intensities. By comparing these two subsampled model ensembles with the other ensembles of different forcing scenarios, we can estimate the signal-to-noise ratio in the return period plots. The supplementary material of Table S2 lists the wettest and driest years for ~~pre-monsoon and monsoon seasons~~ MAM and JJAS over the four different sub-regions.

In order to examine robustness of the return time plots based on weather@home's RCM, HadRM3P model outputs; we compare similar results based on decadal simulations from additional four atmospheric general circulation models (AGCMs) from the HAPPI Tier-1 experiments (Mitchell et al., 2017). All forcings scenarios are available in the four AGCM simulations to do the comparison except for GHG-only scenario. These model ensembles are available with ≥100 members per year with initial condition perturbations however; we have used 98 members per year to compare with HadRM3P results. The basic information about these four AGCMs is given at Supplementary Table S3, while more details and evaluation of these models is available in Chevuturi et al., (2018).

~~We presented the change in the occurrence probability of rainfall event, Risk Ratio (RR) (NAS, 2016) quantified as~~

~~$RR = P_f / P_{cf}$…………………………(iii)~~

In order to quantify changes in the probability of occurrence of extreme rainfall event, we use Risk Ratio (RR), which is calculated as RR = P_f / P_{cf} (NAS, 2016). Here P_f denotes the probability of the event in factual climate including climate change (ACT, HAPPI 1.5 and HAPPI 2.0) and P_{cf} denotes the probability of an event of the same magnitude in a counterfactual climate without anthropogenic climate change (NAT).~~Where probability of the event in the factual climate including climate change (here in ACT, HAPPI 1.5 and HAPPI 2.0 scenarios) is denoted by P_f and the probability of the same event in a counterfactual climate without anthropogenic climate change (here in NAT scenario) is denoted by P_{cf}.~~ But, in case of RR for GHG-only scenario, it is calculated with regard to ACT instead of NAT. We ~~provided~~ quantified the changes in the RRs for four event thresholds ~~in pre-monsoon~~ during MAM and ~~monsoon seasons~~ JJAS with return period of 10, 20, 50 and 100 year over the four sub-regions of Bangladesh.

3 Results and Discussion

3.1 Model Evaluation ~~for Five Day Mean Rainfall~~

~~To explore how pre-monsoon and monsoon rainfall is likely to change in Bangladesh over the four sub-regions, We investigate the annual cycles of five day mean~~ 5-day ~~rainfall under different forcing scenarios in comparison to observations. Five day mean rainfall is used to represent the timescale responsible for river flooding as opposed to daily extremes that cause flash floods primarily in the pre-monsoon season.~~ In Figure 1, ~~annual~~ seasonal cycles of ~~five day mean~~ 5-day rainfall as in the simulations of model ensembles under five different forcing scenarios (ACT, NAT, GHG-only, HAPPI 1.5 and HAPPI 2.0) and two observations (APHRODITE and CPC) are shown. The coloured lines represent the ensemble means, with light-coloured shading representing the 10-90% percentile ranges (only shown for ACT model ensemble and the observations). ~~The annual seasonal cycles are based~~

~~on 5-day rainfall, which is used to represent the timescale responsible for river flooding as opposed to daily extremes that cause flash floods primarily in the pre-monsoon season.~~

~~The annual seasonal cycles of five day mean 5-day rainfall from the different model ensembles are adequately representative of the observed annual seasonal cycles. However, the monsoon JJAS rainfall during JJAS months is underestimated by 25-65 25-50% depending on the observational dataset it is compared with and sub-regions. This the monsoon rainfall bias is higher (up to 50% dry bias) at in the wetter sub-regions of 2 and 4 (see Figs. 1b & d) and lower (up to 30% dry bias) at in the drier sub-regions of 1 and 3 (see Figs. 1a & c). We note that The bias is apparently present in all model scenarios; hence it is unlikely to affect the comparison between model scenarios. We also note that the signal of the change due to the changing climate is relatively small in comparison to the total rainfall. More details regarding the model's performance over can be found in Rimi et al. (under review). The differences between the forcing scenarios throughout the annual seasonal rainfall cycle are discussed below.~~

The seasonal cycles of 5-day rainfall from the different model ensembles are adequately representative of the observed seasonal cycles. Most of the observed rainfall is found to be within the 10-90% confidence intervals of the model data. We find an early monsoon onset in the model simulations, which is also reported in previous studies (e.g., in Caesar et al., 2015; Fahad et al., 2017; Janes and Bhaskaran, 2012). However, JJAS rainfall is underestimated by 25-50% depending on the observational dataset and sub-regions. This bias is higher (up to 50% dry bias) in the wetter sub-regions of 2 and 4 (Figs. 1b & d) and lower (up to 30% dry bias) in the drier sub-regions of 1 and 3 (Figs. 1a & c). Underestimation of JJAS rainfall is reported in other model based studies over Indian monsoon region (Goswami et al., 2014; Kumar and Dimri, 2019; Saha et al., 2014) and specifically in Bangladesh (Caesar and Janes, 2018; Islam, 2009; Macadam and Janes, 2017).

The bias is apparently present in all model scenarios used in this study; hence it is unlikely to affect the comparison between model scenarios. We also note that the signal of the change due to the changing climate is relatively small in comparison to the total rainfall. Therefore, the model is considered fit for purpose in assessing the potential impacts of climate change on extreme rainfall events. The differences between the forcing scenarios throughout the ~~annual~~ seasonal rainfall cycle are discussed below.

3.2 Impact of Climate Change and Aerosol Reduction on Seasonal Mean Rainfall

Our results suggest that changes in mean rainfall due to global warming are significant for both ~~the pre-monsoon~~ MAM and JJAS ~~monsoon periods~~, and that aerosols play an important role in determining the magnitude of future changes (Figs. 2 & 3). Based on PC, these changes are particularly evident ~~in the pre-monsoon season~~ during MAM ~~based on PC~~, yet a smaller PC during ~~the monsoon season~~ JJAS can still have a significant impact given the magnitude of rainfall. Relative changes between pairs of forcing scenarios show large spatial variability over Bangladesh and the wider central South Asia region, although they suggest a general wetting trend across Bangladesh for both 1.5°C and 2.0°C ~~degree~~ warmer worlds.

During MAM ~~the pre-monsoon season (Fig. 2)~~, results show a non-linear response to temperature change in the PC over the eastern part of South Asia (Figs. 2a, b, & c) that is likely to be caused at least in part by the response for aerosols in ~~the~~ Fig. 2d. The present-day ~~(~~ACT~~)~~ PC relative to ~~the pre-industrial period (~~NAT~~)~~ indicates that ~~the~~ mean ~~pre-monsoon~~ MAM rainfall is reduced by 15-30% over the eastern parts of South Asia and increased by 15-25% over the northern parts Bangladesh (Fig. 2a). Figure 2d shows the spatial distribution of the "omitted" aerosol induced rainfall over the South Asia region. Once aerosol levels drop to ~~1/3th~~ one-third of its current values (following the RCP2.6 protocol, IPCC, 2013), an increase of up to 20% in ~~the pre-monsoon~~ MAM rainfall is very likely to happen over most parts of South Asia~~n~~ region. Associated with this increased rainfall, ~~the~~

PC relative to ~~present-day (~~ACT~~)~~ in ~~a 1.5°C warmer world (~~HAPPI 1.5~~)~~ increases up to 20% over South Asia (Fig. 2b), with Bangladesh being the region where the aerosol effect dominates the total change (Figs. 2f & h). Across Bangladesh, our results indicate that ~~the pre-monsoon~~ MAM rainfall increases approximately linearly with temperature, suggesting a ~~primary~~ relevant role for thermodynamic effects and ~~only a secondary~~ perhaps a smaller role for dynamic changes as far as our HadRM3P model results are concerned. By linear response, we meant steady and gradual increase in the climate change impact on rainfall from one forcing scenario to another due the warming effects starting from NAT to ACT, ACT to HAPPI 1.5 and HAPPI 1.5 to HAPPI 2.0. The additional warming effects in ~~a 2.0°C world of (~~HAPPI 2.0~~)~~ increase the mean ~~pre-monsoon~~ MAM rainfall by an extra 10-20% over Bangladesh (Fig. 2g), in contrast to other parts of Asia. We note that our conjectures are speculative at this point, yet likely based on established research into monsoon dynamics (e.g., Bollasina et al. 2011).

Using other RCM projections (based on RCP8.5), Fahad et al. (2017) pointed out that ~~pre-monsoon seasonal~~ MAM mean rainfall may ~~significantly~~ increase by up to 20% relative to their baseline period (1971–2000) over the eastern mountainous region of Bangladesh, in line with our results for 1.5 and 2.0°C warming. However, the fact that the northern parts of India show very non-linear behaviour with regard to rainfall PC in response to the combined GHG and aerosol-related radiative forcing (Figs. 2a-d) is indicative of circulatory, dynamic shifts with stronger warming. ~~This is opposed to a more linear thermodynamic response which usually scales with 20-40% of Clausius-Clapeyron for non-extreme rainfall.~~

The PC of mean ~~monsoon seasonal~~ JJAS rainfall (Fig. 3a) in ~~the present-day climate (~~ACT~~)~~ relative to ~~pre-industrial period (~~NAT~~) (Fig. 3a)~~ indicates a weakening monsoon over central India and strengthening of the monsoon over Bangladesh and north-east India (10-15% increase ~~in mean monsoon seasonal rainfall~~). Evidence for reduced ~~monsoon~~ JJAS rainfall amounts over the last few decades in ~~the~~ South Asia~~n~~ region is also found in the observational records (Bollasina et al., 2011; Srivastava et al., 2010; Turner and Annamalai, 2012; Wang et al., 2012). In contrast, the CMIP5 models simulate about 2.3% increase in rainfall per degree of warming for the Indian summer monsoon (Menon et al., 2013) due to an increase in moisture availability in a warmer world. These conflicting results can be attributed to an underestimated aerosol effect in many CMIP5 models. Subsampling those models that include indirect aerosol effects helps to resolve the discrepancy (Bollasina et al., 2011; Turner and Annamalai, 2012). ~~We highlight that HadRM3P model estimates the aerosol effects satisfactorily (Haustein et al., in progress); besides the results are largely consistent with observed rainfall trends.~~

The most ~~significant~~ important change in the PC occurs in ~~the~~ ~~1.5°C warmer world~~ HAPPI1.5 relative to ACT ~~the current actual world~~ (Fig. 3b). Comparing HAPPI 1.5 and 2.0~~°C~~, we find an additional increase in ~~the~~ mean ~~monsoon~~ JJAS rainfall but of lower magnitude (a further 10 to 20% increase; Fig. 3c). We find a very strong drying tendency during JJAS due to ~~the presence of~~ anthropogenic aerosols ~~relative to ACT~~ over most parts of South Asia (Fig. 3a). Correspondingly, the “committed” rainfall increase, which will be realised once aerosol emissions are reduced (Fig. 3d), is in the order of 15-30%. This means that the observed drying is entirely caused by the aerosols that have overcompensated~~, and hence efficiently masked,~~ the GHG induced rainfall increase. In Bangladesh (Figs. 3e-h), the aerosol effect is less strong and GHG induced intensification of summer monsoon rainfalls have already increased the risk of more intense rain. The Standardized Precipitation Index (SPI) ~~index~~ analysis for the pre-monsoon and monsoon seasons (Supplementary Figs. S1 & 2) corroborates our results from the PC analysis.

In addition to PC and SPI analyses, we looked at the absolute rainfall (Figs. 4 & 5) for all five forcing scenarios during MAM and JJAS (median, as well as the 25-75th percentiles of seasonal mean rainfall) to explain the variability in the mean of absolute rainfall relative to the change between scenarios over the four sub-regions in Bangladesh (for locations of the sub-regions, see boxes in Figs. 2e & 3e). ~~Changes in the mean absolute rainfall are much more pronounced over sub-region 1 and 2 during pre-monsoon season (see Fig. 4 a & c), whereas smaller absolute changes occur in sub-region 3 and 4 during monsoon season only~~

~~(Fig. 5 b & d).~~ Changes in mean absolute rainfall are much more pronounced over sub-regions 1 and 2, where both MAM and JJAS rainfall exhibit clear shifts from one forcing to another forcing scenario (Fig. 4). On the other hand, over sub-regions 3 and 4, only JJAS rainfall exhibited a robust shift (Fig. 5 b & d). The absolute aerosol effect is strongest in summer during JJAS, yet the relative change is smaller which is in line with lower rainfall PC as discussed above. Most importantly, ~~however,~~ aerosols play a dominant role in all sub-regions and seasons, except for MAM rainfall over sub-region 3 and 4. Despite more effective aerosol removal from the atmosphere by means of wet deposition during JJAS ~~the monsoon season~~, high regional emission rates prevent drastic reductions of the aerosol optical depth. ~~As a result~~ Consequently, direct and indirect aerosol effects, accompanied by feedbacks such as reduced lapse rate, ~~increased atmospheric stability,~~ reduced boundary layer turbulence, or a modified land-sea circulation, remain to be a potent driver for changing monsoonal rainfall amounts.

For future warming scenarios of ~~(~~HAPPI 1.5 and HAPPI 2.0~~)~~ compared to ~~current actual climate conditions (~~ACT~~)~~, we find robust linear ~~(absolute)~~ increase in (absolute) rainfall in almost all sub-regions and seasons. We notice a persistent change with increase in absolute mean rainfall from ACT to HAPPI 1.5 and HAPPI 1.5 to HAPPI 2.0. Conversely, we find no clear ~~trend~~ shifts between NAT, ACT and HAPPI 1.5 ~~in~~ during MAM ~~in~~ over sub-region 3 and 4 (Figs. 5a & c). While aerosol effects are consistent with those in other regions, the GHG induced rainfall is hampered, likely due to dynamic changes such as a delayed onset of the monsoon in response to warming. The proximity to the Indian Ocean may also be a contributing factor. While the atmosphere can hold more moisture, the slower ocean warming stabilises the atmosphere over sea in the same way aerosols stabilise the atmosphere over land.

Impact of climate change and aerosol reduction on seasonal mean rainfall (as in PC, SPI and absolute) is in agreement with the findings in the ~~annual~~ seasonal cycles (Fig. 1) presented before. As shown in Fig. 1, the monsoon onset in sub-region 3 and 4 (Figs. 1c & d) does not change notably under different forcing scenarios as far as 5-day ~~mean~~ rainfall is concerned. Otherwise, the aerosol and GHG induced response is consistent with the conclusions based on the spatial maps across the four sub-regions. Sub-regions 1 and 2 show considerable changes in rainfall strength during MAM ~~the pre-monsoon season~~, with an earlier onset in the HAPPI 2.0 scenario ~~in~~ over sub-region 2. The most pronounced change is simulated ~~during~~ at the peak of ~~the~~ monsoon season, in early June ~~in~~ over sub-region 2, with an associated increase in magnitude of almost ~~1/3~~ one-third between NAT and HAPPI 2.0. It is noteworthy that this increase in rainfall is very linear with progressively warmer climate conditions (Fig. 1b).

3.3 Extreme Rainfall Events

An analysis of changes in extreme rainfall events suggests that Bangladesh is likely to experience significantly higher ~~frequencies of occurrence~~ magnitude ~~for~~ of 1 and 5-day rainfall events (Figs. 6-9 and S3-S6) during both pre-monsoon and monsoon seasons across all sub-regions ~~(Figs. 6-9)~~ for a 1.5°C change. ~~with~~ The only exceptions ~~of~~ included ~~pre-monsoon~~ MAM rainfall events over sub-region 4 (Fig. 7b)~~;~~ and ~~monsoon~~ JJAS rainfall events over sub-region 3 ~~and 4~~ (Fig~~s~~. 9a ~~& b~~). In contrast, changes between HAPPI 1.5 and HAPPI 2.0 are only significant in JJAS over sub-regions 1 and 2 ~~in summer monsoon season~~ (Figs. 8a & b). ~~The signal-to-noise ratio is higher in the monsoon season across all sub-regions with the lowest and highest ratio in sub-region 1 and 3, respectively (Figs. 8a & 9a).~~ Overall, the signal-to-noise ratio is higher across all sub-regions, during JJAS compared to that during MAM. During MAM, the highest and lowest signal-to-noise ratio is over sub-region 1 and 3, respectively (Figs. 6a & 7a). On the other hand, during JJAS, we find the highest and lowest signal-to-noise ratio is over sub-region 3 and 1, respectively (Figs. 9a & 8a). The lower the ratio, the more difficult it is to establish causality as natural variability due to ENSO or circulation anomalies is higher.

~~In summary, the~~ The most linear rainfall response to warming is simulated in sub-region 2 in MAM and JJAS (Figs. 6b & 8b), with aerosols masking approximately 50% of the increased risk with regard to 1-in-100-year NAT return time. Hence future rainfall in sub-region 2 continues to increase, with accelerated pace once aerosol levels drop significantly. Sub-region 1 is likely to receive more extreme rainfall as well with continued warming, with strong increases once aerosol levels drop. Sub-regions 1 and 2 are equally sensitive to aerosols, yet dynamic feedback processes ~~appear to~~ might partially counter the thermodynamic increase in rainfall risk with continued warming.

Figures 10 and 11 give simple illustration for the change in risk ratios, which remarkably vary with seasons (pre-monsoon and monsoon) as well as locations (sub-regions of 1-4) and also indicate how aerosols impact risk ratios. Supplementary material of Table ~~S3~~ S4 and S5 present the risk ratios with associated uncertainty ranges for ~~both seasons~~ MAM and JJAS rainfall over four sub-regions, respectively. Figure 10 demonstrates that there is noticeable masking effect of aerosols during MAM that repress the change between NAT and ACT worlds at sub-region 1. Hence, present-day risk for MAM rainfall event has not changed (see RR for ACT/NAT in Fig. 10a). But then the risk of extreme rainfall event with respect to 1-in-100-year NAT return time increase by a factor of 4 (with uncertainty range 2.0-7.0) in a 1.5°C world (see RR for HAPP1.5/NAT in Fig. 10a). In contrast, the aerosol masking effect during MAM is minimal at sub-region 2; leading to a robust change between NAT and ACT worlds (see RR for ACT/NAT in Fig. 10b).

We find persistent increase in the RRs for JJAS extreme rainfall events at the sub-regions 2 and 4. At sub-region 2, risk of JJAS extreme rainfall event with respect to 1-in-100-year NAT return time increases 3-fold (with uncertainty range 1-4) in a 1.5°C world and then 4.6-fold (with uncertainty range 2.9-7.2) in a 2.0°C world (see RRs for HAPP1.5/NAT and HAPP2.0/NAT in Fig. 10d). At sub-region 4 (Fig. 11d), where current risks of JJAS extreme rainfall events are already increased 3.9 times (with uncertainty range 2.6-5.8) with respect to 1-in-100-year NAT return time; the risk for similar event increases 4.1 times (with uncertainty range 2.2-5.3) in a 1.5°C world and 5.5 times in a 2.0°C world (with uncertainty range 3.5-7.8).

4 Conclusions

Results of the weather@home HadRM3P South Asia regional model suggest that both, 1.5°C and 2.0°C warming are projected to increase seasonal mean and extreme rainfall probabilities during the pre-monsoon and monsoon seasons across Bangladesh. These increases are likely to be amplified by a reduction in aerosols, consistent with previous findings (e.g., Samset et al., 2018). These projected changes have important implications for agricultural yields and associated economic losses, particularly during the pre-monsoon season. In contrast, property damage is more likely to occur during the monsoon season when large inhabited areas are inundated on a regular basis. We find that there are large spatial variations in the patterns of changes in the relative risks of extreme rainfall in Bangladesh.

~~In conclusion, the drier~~ ~~s~~ Sub-regions 1 and 2 shows ~~a greater masking effect from the aerosols~~ an enhanced susceptibility to aerosols during the pre-monsoon season; whereas, ~~the wetter~~ sub-regions 3 and 4 ~~have~~ show a smaller aerosol ~~effect~~ sensitivity ~~particularly~~ during the monsoon season. Aerosols have reduced the absolute daily rainfall amount by up to 1mm (~ 5-10%) during the monsoon season in sub-region 1 and 2, comparable to the simulated rainfall change in a future 2.0°C warming scenario. This is in line with a growing array of research that has shown that anthropogenic aerosols play a substantial role in modulating the strength of the monsoon in South Asia (Bollasina et al., 2011, 2013; Lau and Kim, 2010; Ramanathan et al., 2005). As far as other regions in South Asia are concerned, our results imply that the present-day decline in the mean monsoon seasonal rainfall can be explained by the existing atmospheric aerosols impacts, which offsets the GHG-induced global warming effects. Future aerosol removal from the atmosphere will unmask the GHG induced rainfall increase with surprisingly fast changes in risk due to the non-linear nature of the imposed external forcing contributions (e.g., over sub-region 1 in pre-monsoon season). For that reason we emphasize that the impacts of aerosol reductions on the changing risks of extreme rainfall events should be considered for future risk assessments.

Considering the importance of the climate change impacts found in sub-region 1 and 2 for MAM and JJAS rainfall extremes, Figs. 12 and 13 demonstrate how robust the HadRM3P results are compared to four other HAPPI AGCMs of MIROC5, ETH_CAM4, CanAM4 and NorESM1 models. Similar comparisons for other sub-regions and seasons are presented at the supplementary material for brevity (in Figs. S7 - S12). For MAM rainfall extremes over sub-region 1, HadRM3P, MIROC5 and NorESM1 models suggest increasing risks but ETH_CAM4 and CanAM4 models show increasing risks only for a 2.0°C warmer climate condition. MIROC5 model shows a linear progression of MAM rainfall risks, increasing from NAT to Act and then from ACT to 1.5° and 2.0°C warmer conditions (Fig. 12b). In contrast, HadRM3P model shows a non-linear change in the MAM rainfall risks with nearly no increase between NAT and ACT but then a drastic increase in warmer scenarios (Fig. 12a). Since the other HAPPI AGCMs do not provide a GHG-only scenario, we can only infer causality of potential non-linear changes between the warming scenarios from HadRM3P model in this case. For JJAS rainfall extremes over sub-region2, all five models suggest increasing risks in warmer conditions (see Figs. 13a-e). However intensities of rainfall events vary within different models. NorESM1 model includes updated module for aerosols and aerosol–cloud–radiation interactions (Kirkevåg et al., 2013), as a consequent, we find that for JJAS rainfall extremes HadRM3P model results show better agreement with this model in terms of both increasing risks and rainfall intensities (compare Figs. 13a &e).

~~Finding of this study implies that policy-makers and relevant stakeholders not only need to take distinctively different regional responses in extreme rainfall into account, but also the non-linearity in the response. Relying on observed changes can be deeply misleading, creating an unwarranted sense of security. Our study highlights that preparedness for more frequent extremes is key in the northern part of Bangladesh during both the pre-monsoon and the monsoon season. The magnitude of change exceeds the current internal year-to-year variability in the associated sub-regions 1 and 2 during both pre-monsoon MAM and monsoon JJAS seasons. While additional regional model experiments are needed to confirm the weather@home model results, available data from other HAPPI GCMs point in the same direction (Chevuturi et al., 2018; Lee et al., 2018). While additional regional model experiments are needed to confirm the weather@home model results, our analysis of available data from other HAPPI GCMs point in the same direction for seasonal extreme rainfall events in Bangladesh. Similar findings are also reported for the South Asia region (e.g., Chevuturi et al., 2018; Lee et al., 2018). However, since they do not allow for a quantification of the aerosol effect, we call for more nuanced experiments in that regard in the future. Since the other HAPPI models do not provide a GHG-only scenario, we can only infer causality of potential non-linear changes between the warming scenarios from weather@home.~~

This study for the first time presents a multi-model assessment of both current and future changes in the risks of seasonal extreme rainfall events, considering anthropogenic climate change drivers of GHGs and aerosols, at sub-regional local scales in Bangladesh. These projected changes have important implications for agricultural yields and associated economic losses, particularly during the pre-monsoon season. For example, at north-east Bangladesh, in 2017, pre-monsoon extreme rainfall caused the earliest flash flood since 2000. Consequent damage of nearly harvestable rice crop in turn, caused the highest price hike in the following year. Anthropogenic climate change drivers are found to make this extreme rainfall event twice as likely (Rimi et al., 2019b). In contrast, during the monsoon season, property damage is more likely to occur when large inhabited areas are inundated on a regular basis. Finding of this study implies that policy-makers and relevant stakeholders not only need to take distinctively different regional responses in extreme rainfall into account, but also the non-linearity in the response. Relying on observed changes can be deeply misleading, creating an unwarranted sense of security. Our study highlights that preparedness for more frequent extremes is key in the northern part of Bangladesh during both the pre-monsoon and the monsoon season. While additional regional model experiments are needed to confirm the weather@home model results, our analysis of available data from other HAPPI GCMs point in the same direction for seasonal extreme rainfall events in Bangladesh. Similar findings are also reported for the South Asia region (e.g., Chevuturi et al., 2018; Lee et al., 2018). However, since they do not allow for a quantification of the aerosol effect, we call for more nuanced experiments in that regard in the future.

Data/Code availability

Observation data set of APHORODITE is available for download at http://aphrodite.st.hirosaki-u.ac.jp/products.html and CPC can be downloaded from https://climexp.knmi.nl/select.cgi?id=someone@somewhere&field=prcp_cpc_daily. The additional four HAPPI AGCM simulation data can be accessed at http://portal.nersc.gov/c20c/data/. Analysis code is available upon request from the corresponding author.

Supplement

The supplement related to this article is available online at: ……………………………………………………….

Author contributions

Ruksana H. Rimi's contribution towards this work was performed as part of her DPhil research project. ~~All results were analysed and plotted by Ruksana H. Rimi with advice from Myles R. Allen, Karsten Haustein, and Emily Barbour.~~ Karsten Haustein generated and extracted the weather@home model data. Sihan Li and Sarah N. Sparrow prepared and distributed the computational simulations to generate the data used in the study onto the weather@home system. David C.H. Wallom manages operation of the weather@home/climateprediction.net infrastructure which was used to generate the data. All results were analysed and plotted by Ruksana H. Rimi with advice from Myles R. Allen, Karsten Haustein, and Emily Barbour. The paper was written by Ruksana H. Rimi, with edits from all co-authors.

Acknowledgments

We would like to thank the Met Office Hadley Centre PRECIS team for their technical and scientific support for the development and application of weather@home. We would like to thank our colleagues at the Oxford eResearch Centre for their technical expertise. We acknowledge the use of the observation datasets of APHRODITE and CPC. Finally, we would like to thank all the volunteers who have donated their computing time to climateprediction.net and weather@home. ~~The authors declare that they have no conflict of interest.~~

Competing interests

The authors declare that they have no conflict of interests.

References

Ahmed, M. R., Rahaman, K. R., Kok, A. and Hassan, Q. K.: Remote sensing-based quantification of the impact of flash flooding on the rice production: A case study over Northeastern Bangladesh, Sensors (Switzerland), 17(10), doi:10.3390/s17102347, 2017.

Ali, R. M. E., Tunbridge, L. W., Bhasin, R. K., Akter, S., Khan, M. M. H. and Uddin, M. Z.: Landslides susceptibility of chittagong city, bangladesh and development of landslides early warning system, in Landslide Science for a Safer

Geoenvironment, vol. 1, pp. 423–429., 2014.

Allen, M.: Do-it-yourself climate prediction, Nature, 401(6754), 642, doi:10.1038/44266, 1999.

Banglapedia: River and Drainage system, Banglapedia- Natl. Encycl. Bangladesh [online] Available from: http://en.banglapedia.org/index.php?title=River_and_Drainage_System, 2012.

Bollasina, M. A., Ming, Y. and Ramaswamy, V.: Anthropogenic aerosols and the weakening of the south asian summer monsoon, Science (80-.)., 334(6055), 502–505, doi:10.1126/science.1204994, 2011.

Bollasina, M. A., Ming, Y. and Ramaswamy, V.: Earlier onset of the Indian monsoon in the late twentieth century: The role of anthropogenic aerosols, Geophys. Res. Lett., 40(14), 3715–3720, doi:10.1002/grl.50719, 2013.

Caesar, J. and Janes, T.: Regional climate change over South Asia, in Ecosystem Services for Well-Being in Deltas: Integrated Assessment for Policy Analysis, pp. 207–221., 2018.

Caesar, J., Janes, T., Lindsay, A. and Bhaskaran, B.: Temperature and precipitation projections over Bangladesh and the upstream Ganges, Brahmaputra and Meghna systems, Environ. Sci. Process. Impacts, 17(6), 1047–1056, doi:10.1039/C4EM00650J, 2015.

Chen, M., Shi, W., Xie, P., Silva, V. B. S., Kousky, V. E., Higgins, R. W. and Janowiak, J. E.: Assessing objective techniques for gauge-based analyses of global daily precipitation, J. Geophys. Res. Atmos., 113(4), doi:10.1029/2007JD009132, 2008a.

Chen, M., Xie, P. and NOAA Climate Prediction Center(CPC): CPC Gauge-Based Analysis of Global Daily Precipitation, in Western Pacific Geophysics Meeting, Cairns, Australia, 29 July - 1 August, 2008. [online] Available from: ftp://ftp.cpc.ncep.noaa.gov/precip/CPC_UNI_PRCP/GAUGE_GLB/DOCU/Chen_et_al_2008_Daily_Gauge_Anal.pdf, 2008b.

Chevuturi, A., Klingaman, N. P., Turner, A. G. and Hannah, S.: Projected Changes in the Asian-Australian Monsoon Region in 1.5°C and 2.0°C Global-Warming Scenarios, Earth's Futur., 6(3), 339–358, doi:10.1002/2017EF000734, 2018.

Donlon, C. J., Martin, M., Stark, J., Roberts-Jones, J., Fiedler, E. and Wimmer, W.: The Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) system, Remote Sens. Environ., 116, 140–158, doi:10.1016/j.rse.2010.10.017, 2012.

Endo, H., Kitoh, A., Ose, T., Mizuta, R. and Kusunoki, S.: Erratum: Future changes and uncertainties in Asian precipitation simulated by multiphysics and multi-sea surface temperature ensemble experiments with high-resolution Meteorological Research Institute atmospheric general circulation models (MRI-AGCMs) (Jo, J. Geophys. Res. Atmos., 118(5), 2303, doi:10.1002/jgrd.50267, 2013.

Essery, R. L. H., Best, M. J., Betts, R. A., Cox, P. M. and Taylor, C. M.: Explicit representation of subgrid heterogeneity in a GCM land surface scheme, J. Hydrometeorol., 4(3), 530–543, doi:10.1175/1525-7541(2003)004<0530:EROSHI>2.0.CO;2, 2003.

Fahad, M. G. R., Saiful Islam, A. K. M., Nazari, R., Alfi Hasan, M., Tarekul Islam, G. M. and Bala, S. K.: Regional changes of precipitation and temperature over Bangladesh using bias-corrected multi-model ensemble projections considering high-emission pathways, Int. J. Climatol., doi:10.1002/joc.5284, 2017.

Faust, E.: Rapid attribution: Is climate change involved in an extreme weather event?, [online] Available from: https://www.munichre.com/topics-online/en/2017/topics-geo/rapid-attribution, 2017.

Fung, F., Lopez, A. and New, M.: Water availability in +2 C and +4 C worlds, Philos. Trans. R. Soc. A Math. Phys. Eng. Sci., 369(1934), 99–116, doi:10.1098/rsta.2010.0293, 2011.

Goswami, B. B., Deshpande, M., Mukhopadhyay, P., Saha, S. K., Rao, S. A., Murthugudde, R. and Goswami, B. N.: Simulation of monsoon intraseasonal variability in NCEP CFSv2 and its role on systematic bias, Clim. Dyn., 43(9–10), 2725–2745, doi:10.1007/s00382-014-2089-5, 2014.

Guillod, B. P., Jones, R. G., Bowery, A., Haustein, K., Massey, N. R., Mitchell, D. M., Otto, F. E. L., Sparrow, S. N., Uhe, P., Wallom, D. C. H., Wilson, S. and Allen, M. R.: Weather@home 2: Validation of an improved global-regional climate modelling system, Geosci. Model Dev., 10(5), 1849–1872, doi:10.5194/gmd-10-1849-2017, 2017.

Guo, L., Highwood, E. J., Shaffrey, L. C. and Turner, A. G.: The effect of regional changes in anthropogenic aerosols on rainfall of the East Asian Summer Monsoon, Atmos. Chem. Phys., 13(3), 1521–1534, doi:10.5194/acp-13-1521-2013, 2013.

Gutro, R.: Bangladesh's Heavy Rainfall Examined With NASA's IMERG, Nasa Gpm [online] Available from: https://www.nasa.gov/feature/goddard/2017/bangladeshs-heavy-rainfall-examined-with-nasas-imerg (Accessed 14 November 2017), 2017.

Hauser, M., Gudmundsson, L., Orth, R., Jézéquel, A., Haustein, K., Vautard, R., van Oldenborgh, G. J., Wilcox, L. and Seneviratne, S. I.: Methods and Model Dependency of Extreme Event Attribution: The 2015 European Drought, Earth's Futur., 5(10), 1034–1043, doi:10.1002/2017EF000612, 2017.

Haustein, K., Uhe, P. F., Rimi, R. H., Islam, A. S. and Otto, F. E. L.: Is the wettest place on Earth getting wetter?, Geophys. Res. Lett., n.d.

Hossain, A. N. H. A.: Flood management. [online] Available from: http://www.apfm.info/publications/casestudies/cs_bangladesh_sum.pdf, 1998.

IPCC, 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. [online] Available from: http://scholar.google.nl/scholar?hl=nl&q=climate+change&btnG=&lr=&oq=climate+ca#2, 2013.

Islam, M. N.: Rainfall and Temperature Scenario for Bangladesh, Open Atmos. Sci. J., 3(1), 93–103, doi:10.2174/1874282300903010093, 2009.

Janes, T. and Bhaskaran, B.: Evaluation of regional model performance in simulating key climate variables over Bangladesh, Met Office, Exeter, United Kingdom., 2012.

Jones, A., Roberts, D. L., Woodage, M. J. and Johnson, C. E.: Indirect sulphate aerosol forcing in a climate model with an interactive sulphur cycle, J. Geophys. Res. Atmos., 106(D17), 20293–20310, doi:10.1029/2000JD000089, 2001.

Kirkevåg, A., Iversen, T., Seland, Ø., Hoose, C., Kristjánsson, J. E., Struthers, H., Ekman, A. M. L., Ghan, S., Griesfeller, J., Nilsson, E. D. and Schulz, M.: Aerosol–climate interactions in the Norwegian Earth System Model – NorESM1-M, Geosci. Model Dev., 6(1), 207–244, doi:10.5194/gmd-6-207-2013, 2013.

Klimont, Z., Smith, S. J. and Cofala, J.: The last decade of global anthropogenic sulfur dioxide: 2000-2011 emissions, Environ. Res. Lett., 8(1), doi:10.1088/1748-9326/8/1/014003, 2013.

Kripalani, R. H., Oh, J. H., Kulkarni, A., Sabade, S. S. and Chaudhari, H. S.: South Asian summer monsoon precipitation variability: Coupled climate model simulations and projections under IPCC AR4, Theor. Appl. Climatol., 90(3–4), 133–159, doi:10.1007/s00704-006-0282-0, 2007.

Kumar, D. and Dimri, A. P.: Sensitivity of convective and land surface parameterization in the simulation of contrasting monsoons over CORDEX-South Asia domain using RegCM-4.4.5.5, Theor. Appl. Climatol., doi:10.1007/s00704-019-02976-9, 2019.

Kumar, D., Arya, D. S., Murumkar, A. R. and Rahman, M. M.: Impact of climate change on rainfall in Northwestern Bangladesh using multi-GCM ensembles, Int. J. Climatol., 34(5), 1395–1404, doi:10.1002/joc.3770, 2014.

Kumar, K. K., Kamala, K., Rajagopalan, B., Hoerling, M. P., Eischeid, J. K., Patwardhan, S. K., Srinivasan, G., Goswami, B. N.

and Nemani, R.: The once and future pulse of Indian monsoonal climate, Clim. Dyn., 36(11–12), 2159–2170, doi:10.1007/s00382-010-0974-0, 2011.

Lau, W. K. M. and Kim, K. M.: Fingerprinting the impacts of aerosols on long-term trends of the Indian summer monsoon regional rainfall, Geophys. Res. Lett., 37(16), n/a-n/a, doi:10.1029/2010GL043255, 2010.

Lee, D., Min, S.-K., Fischer, E. M., Shiogama, H., Bethke, I., Lierhammer, L. and Scinocca, J.: Impacts of half a degree additional warming on the Asian summer monsoon rainfall characteristics, Environ. Res. Lett., doi:10.1088/1748-9326/aab55d, 2018.

Li, Z., Lau, W. K. M., Ramanathan, V., Wu, G., Ding, Y., Manoj, M. G., Liu, J., Qian, Y., Li, J., Zhou, T., Fan, J., Rosenfeld, D., Ming, Y., Wang, Y., Huang, J., Wang, B., Xu, X., Lee, S. S., Cribb, M., Zhang, F., Yang, X., Zhao, C., Takemura, T., Wang, K., Xia, X., Yin, Y., Zhang, H., Guo, J., Zhai, P. M., Sugimoto, N., Babu, S. S. and Brasseur, G. P.: Aerosol and monsoon climate interactions over Asia, Rev. Geophys., 54(4), 866–929, doi:10.1002/2015RG000500, 2016.

Macadam, I. and Janes, T.: Validation of Regional Climate Model simulations for the DECCMA project, DECCMA Working Paper, Deltas, Vulnerability and Climate Change: Migration and Adaptation, IDRC Project Number 107642, www.deccma.com., 2017.

Massey, N., Jones, R., Otto, F. E. L., Aina, T., Wilson, S., Murphy, J. M., Hassell, D., Yamazaki, Y. H. and Allen, M. R.: Weather@Home-Development and Validation of a Very Large Ensemble Modelling System for Probabilistic Event Attribution, Q. J. R. Meteorol. Soc., 141(690), 1528–1545, doi:10.1002/qj.2455, 2015.

Menon, A., Levermann, A., Schewe, J., Lehmann, J. and Frieler, K.: Consistent increase in Indian monsoon rainfall and its variability across CMIP-5 models, Earth Syst. Dyn. Discuss., 4(1), 1–24, doi:10.5194/esdd-4-1-2013, 2013.

Mitchell, D., James, R., Forster, P. M., Betts, R. A., Shiogama, H. and Allen, M.: Realizing the impacts of a 1.5 °C warmer world, Nat. Clim. Chang., 6(8), 735–737, doi:10.1038/nclimate3055, 2016.

Mitchell, D., AchutaRao, K., Allen, M., Bethke, I., Beyerle, U., Ciavarella, A., Forster, P. M., Fuglestvedt, J., Gillett, N., Haustein, K., Ingram, W., Iversen, T., Kharin, V., Klingaman, N., Massey, N., Fischer, E., Schleussner, C. F., Scinocca, J., Seland, Ø., Shiogama, H., Shuckburgh, E., Sparrow, S., Stone, D., Uhe, P., Wallom, D., Wehner, M. and Zaaboul, R.: Half a degree additional warming, prognosis and projected impacts (HAPPI): Background and experimental design, Geosci. Model Dev., 10(2), 571–583, doi:10.5194/gmd-10-571-2017, 2017.

Murshed, S. B., Islam, A. K. M. and Khan, M. S. A.: Impact of climate change on rainfall intensity in Bangladesh, Dhaka, Bangladesh. [online] Available from: http://teacher.buet.ac.bd/akmsaifulislam/reports/Heavy_Rainfall_report.pdf, 2011.

National Academies of Sciences, Engineering, and M.: Attribution of Extreme Weather Events in the Context of Climate Change, National Academies Press, Washington, D.C., 2016.

Nirapad: Bangladesh: Flash Flood Situation - April 19, 2017, Situat. Rep., 7 [online] Available from: https://reliefweb.int/sites/reliefweb.int/files/resources/Flash_Flood%2C Updated %28April 19%29%2C 2017.pdf (Accessed 14 November 2017), 2017.

Nowreen, S., Murshed, S. B., Islam, A. K. M. S., Bhaskaran, B. and Hasan, M. A.: Changes of rainfall extremes around the haor basin areas of Bangladesh using multi-member ensemble RCM, Theor. Appl. Climatol., 119(1–2), 363–377, doi:10.1007/s00704-014-1101-7, 2015.

Otto, F. E. L.: Attribution of Weather and Climate Events, Annu. Rev. Environ. Resour., 42(1), 627–646, doi:10.1146/annurev-environ, 2017.

Paul, R. and Hussain, Z.: Landslide, floods kill 156 in Bangladesh, India; toll could rise, Reuters, 14th June [online] Available from: https://uk.reuters.com/article/uk-bangladesh-landslides/landslide-floods-kill-156-in-bangladesh-india-toll-could-rise-idUKKBN1950AG, 2017.

Philip, S., Sparrow, S., Kew, S. F., van der Wiel, K., Wanders, N., Singh, R., Hassan, A., Mohammed, K., Javid, H., Haustein, K., Otto, F. E. L., Hirpa, F., Rimi, R. H., Islam, A. S., Wallom, D. C. H. and van Oldenborgh, G. J.: Attributing the 2017 Bangladesh floods from meteorological and hydrological perspectives, Hydrol. Earth Syst. Sci. Discuss., 1–32, doi:10.5194/hess-2018-379, 2018.

Ramanathan, V., Chung, C., Kim, D., Bettge, T., Buja, L., Kiehl, J. T., Washington, W. M., Fu, Q., Sikka, D. R. and Wild, M.: Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle, Proc. Natl. Acad. Sci., 102(15), 5326–5333, doi:10.1073/pnas.0500656102, 2005.

Rawlani, A. K. and Sovacool, B. K.: Building responsiveness to climate change through community based adaptation in Bangladesh, Mitig. Adapt. Strateg. Glob. Chang., 16(8), 845–863, doi:10.1007/s11027-011-9298-6, 2011.

Rimi, R. H., Haustein, K., Barbour, E. J., Jones, R. G., Sparrow, S. N. and Allen, M. R.: Evaluation of a large ensemble regional climate modelling system for extreme weather events analysis over Bangladesh, Int. J. Climatol., 39(6), 2845–2861, doi:10.1002/joc.5931, 2019a.

Rimi, R. H., Haustein, K., Barbour, E. J. and Allen, M. R.: Risks of Pre-Monsoon Extreme Rainfall Events of Bangladesh: Is Anthropogenic Climate Change Playing a Role?, Bull. Am. Meteorol. Soc., 100(1), S61–S65, doi:10.1175/BAMS-D-18-0152.1, 2019b.

Saha, S. K., Pokhrel, S., Chaudhari, H. S., Dhakate, A., Shewale, S., Sabeerali, C. T., Salunke, K., Hazra, A., Mahapatra, S. and Rao, A. S.: Improved simulation of Indian summer monsoon in latest NCEP climate forecast system free run, Int. J. Climatol., 34(5), 1628–1641, doi:10.1002/joc.3791, 2014.

Samset, B. H., Sand, M., Smith, C. J., Bauer, S. E., Forster, P. M., Fuglestvedt, J. S., Osprey, S. and Schleussner, C. F.: Climate Impacts From a Removal of Anthropogenic Aerosol Emissions, Geophys. Res. Lett., 45(2), 1020–1029, doi:10.1002/2017GL076079, 2018.

Schaller, N., Kay, A. L., Lamb, R., Massey, N. R., Van Oldenborgh, G. J., Otto, F. E. L., Sparrow, S. N., Vautard, R., Yiou, P., Ashpole, I., Bowery, A., Crooks, S. M., Haustein, K., Huntingford, C., Ingram, W. J., Jones, R. G., Legg, T., Miller, J., Skeggs, J., Wallom, D., Weisheimer, A., Wilson, S., Stott, P. A. and Allen, M. R.: Human influence on climate in the 2014 southern England winter floods and their impacts, Nat. Clim. Chang., 6(6), 627–634, doi:10.1038/nclimate2927, 2016.

Schleussner, C. F., Lissner, T. K., Fischer, E. M., Wohland, J., Perrette, M., Golly, A., Rogelj, J., Childers, K., Schewe, J., Frieler, K., Mengel, M., Hare, W. and Schaeffer, M.: Differential climate impacts for policy-relevant limits to global warming: The case of 1.5 °c and 2 °c, Earth Syst. Dyn., 7(2), 327–351, doi:10.5194/esd-7-327-2016, 2016.

Shahid, S.: Rainfall variability and the trends of wet and dry periods in Bangladesh, Int. J. Climatol., 30(15), 2299–2313, doi:10.1002/joc.2053, 2010.

Srivastava, A., Naresh Kumar, S. and Aggarwal, P. K.: Assessment on vulnerability of sorghum to climate change in India, Agric. Ecosyst. Environ., 138(3–4), 160–169, doi:10.1016/j.agee.2010.04.012, 2010.

Stainforth, D. A., Aina, T., Christensen, C., Collins, M., Faull, N., Frame, D. J., Kettleborough, J. A., Knight, S., Martin, A., Murphy, J. M., Piani, C., Sexton, D., Smith, L. A., Splcer, R. A., Thorpe, A. J. and Allen, M. R.: Uncertainty in predictions of the climate response to rising levels of greenhouse gases, Nature, 433(7024), 403–406, doi:10.1038/nature03301, 2005.

Stark, J. D., Donlon, C. J., Martin, M. J. and McCulloch, M. E.: OSTIA: An Operational, high resolution, real time, global sea surface temperature analysis system., in Oceans 2007 - Marine Challenges: Coastline to Deep Sea, pp. 1–4, IEEE., 2007.

Stott, P. A., Stone, D. A. and Allen, M. R.: Human Contribution to the Heat wave of 2003, Nature, 432(7017), 610–614, 2004.

The World Bank: Turn Down Heat: Why a 4 degree warmer world must be avoided. A Report for the World Bank by the Potsdam Institute for Climate Impact Research and Climate Analytics, Washington, DC : World Bank. [online] Available from: http://climatechange.worldbank.org/sites/default/files/Turn_Down_the_heat_Why_a_4_degree_centrigrade_warmer_world_must_be_avoided.pdf, 2012.

Turner, A. G. and Annamalai, H.: Climate change and the South Asian summer monsoon, Nat. Clim. Chang., 2(8), 587–595, doi:10.1038/NCLIMATE1495, 2012.

UNFCCC: Paris Agreement, in 21st Conference of the Parties, vol. 2017, p. 3., 2015.

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J. F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J. and Rose, S. K.: The representative concentration pathways: An overview, Clim. Change, 109(1), 5–31, doi:10.1007/s10584-011-0148-z, 2011.

Wang, B., Liu, J., Yim, P. J. W. S. and Kiefer, T.: Recent change of the global monsoon precipitation (1979 – 2008), Clim. Dyn., 39(5), 1123–1135, doi:10.1007/s00382-011-1266-z, 2012.

Wilks, D. S.: Comparison of three-parameter probability distributions for representing annual extreme and partial duration precipitation series, Water Resour. Res., 29(10), 3543–3549, doi:10.1029/93WR01710, 1993.

Wilks, D. S.: Statistical Methods in the Atmospheric Sciences, Academic Press, 2011., 2011.

Yatagai, A., Kamiguchi, K., Arakawa, O., Hamada, A., Yasutomi, N. and Kitoh, A.: Aphrodite constructing a long-term daily gridded precipitation dataset for Asia based on a dense network of rain gauges, Bull. Am. Meteorol. Soc., 93(9), 1401–1415, doi:10.1175/BAMS-D-11-00122.1, 2012.

Figure captions:

Figure 1. ~~Annual~~ Seasonal cycles of five day mean rainfall under different forcing scenarios over the four sub-regions of Bangladesh. The ~~HadRM3P~~ ACT (black), NAT (green) and GHG-only (orange), ~~and~~ HAPPI 1.5 (blue) and 2.0 (red) ensembles are compared with the observations from APHRODITE (dark purple) and CPC (dark purple). ~~The model can represent the annual cycles as in the observations but monsoon (JJAS) rainfall is underestimated in all sub-regions. A clearly distinguishable shift in the annual cycles of five day mean rainfall from NAT to ACT, from ACT to GHG, from ACT to HAPPI 1.5 and from HAPPI 1.5 to 2.0 forcing scenarios can be seen in sub-region2 only.~~ The model adequately captures the ~~annual~~ seasonal cycle of rainfall compared to observation but underestimates monsoon rainfall. Only over sub-region 2, rainfall is clearly shifting from NAT to ACT, from ACT to GHG-only, from ACT to HAPPI 1.5 and from HAPPI 1.5 to 2.0 forcing scenarios.

Figure 2. Percentage change (PC) in ~~the pre-monsoon (MAM)~~ MAM ~~seasonal~~ mean rainfall between different forcing scenarios. The top row (panels a-d) shows the regional PC over central parts of the South Asia. ~~(SA) while, bottom row (panels e-h) shows the PC over Bangladesh. The four boxes (1-4) on top of the panel e approximately represent the four sub-regions of Bangladesh. These four sub-regions 1-4 are used later for the relative quantification of risks of extreme pre-monsoon rainfall events.~~ a. ~~present-day rainfall PC relative to natural pre-industrial climate~~ ACT rainfall PC relative to NAT over SA b. ~~present-day~~ ACT rainfall PC relative to HAPPI 1.5°C ~~world~~ over SA c. HAPPI 1.5°C ~~world~~ rainfall PC relative to HAPPI 2.0°C ~~world~~ over SA d. ~~present-day~~ ACT rainfall PC relative to GHG-only ~~climate over SA~~. Bottom row (panels e-h) shows PC in the same way but over Bangladesh. The four boxes (1-4) on top of the panel e represent the four sub-regions of Bangladesh.

Figure 3. ~~Percentage change (PC) in the monsoon (JJAS) seasonal mean rainfall between different forcing scenarios. The top row (panels a-d) shows the regional PC over central parts of the South Asia (SA) while, bottom row (panels e-h) shows the PC over~~

~~Bangladesh. The four boxes (1-4) on top of the panel e approximately represent the four sub-regions of Bangladesh. These four sub-regions 1-4 are used later for the relative quantification of risks of extreme monsoon rainfall events. a. present-day rainfall PC relative to natural pre-industrial climate over SA b. present-day rainfall PC relative to 1.5°C world over SA c. 1.5°C world rainfall PC relative to 2.0°C world over SA d. present-day rainfall PC relative to GHG-only climate over SA.~~ Same as Fig. 2, but for JJAS rainfall PC. ~~The~~ This figure shows that the apparently non-linear response between panels of a, b, and c (or, e, f, g) can be explained by the response for ~~aerosols~~ GHG-only (anthropogenic aerosols reduced to pre-industrial levels) in the panel d (or, h).

Figure 4. ~~Mean~~ Seasonal mean rainfall in ~~pre-monsoon~~ MAM (left column) and ~~monsoon~~ JJAS (right column) ~~seasons during MAM and JJAS months~~ over the sub-regions ~~of~~ 1 and 2 (top and bottom row) of Bangladesh. Green, orange, grey, blue and red colours represent ~~the natural (~~NAT~~)~~, ~~actual climate with aerosols reduced to the pre-industrial level (AR)~~ GHG-only, ~~Actual (~~ACT~~)~~, HAPPI 1.5 ~~(1.5)~~ and HAPPI 2.0 ~~(2.0)~~ ensembles respectively. Each panel has different y-scale range to clearly indicate the details of changes in the median values between different model ensembles. The horizontal black line in each box indicates the median value, the bottom and top limits of the box represents the 25^{th} and 75^{th} percentiles respectively. ~~The figure shows that aerosol impacts are distinguishable between the dry sub-region 1 and the wet sub-region 2. There is noticeable masking effect of aerosols that repress the change between NAT and ACT worlds at sub-region 1. In contrast, at sub-region 2, where highest amounts of observed rainfall can clear most of the pollution from the atmosphere, the masking effect in minimal hence, a robust change between NAT and ACT worlds can be seen. In future with additional warming the mean seasonal rainfall increases over both sub-regions but then again over the sub-region 2, we see larger changes in the seasonal mean rainfall.~~ The figure shows that aerosol impacts over both sub-regions 1 and 2 are larger in MAM dry season than that in JJAS wet season.

Figure 5. ~~Mean rainfall in pre-monsoon (left column) and monsoon (right column) seasons during MAM and JJAS months over the sub-regions of 3 (top row) and 4 (bottom row) of Bangladesh. Green, orange, grey, blue and red colours represent the natural (NAT), actual climate with aerosols reduced to the pre-industrial level (AR), Actual (ACT), HAPPI 1.5 (1.5) and HAPPI 2.0 (2.0) ensembles respectively. Each panel has different y-scale range to clearly indicate the details of changes in the median values between different model ensembles. The horizontal black line in each box indicates the median value, the bottom and top limits of the box represents the 25th and 75th percentiles respectively. There is noticeable masking effect of aerosols that repress the change between NAT and ACT worlds at both sub-region 3 and 4 during pre-monsoon season. On the contrary, in monsoon season, large amounts of rainfall can clear most of the pollution from the atmosphere; so, the masking effect is minimal, hence, a clear change between NAT and ACT worlds is happening. In future with additional warming the mean seasonal rainfall increases over both sub-regions but, larger changes occur in the mean rainfall in monsoon season.~~ Same as Fig. 4, but for sub-regions 3 and 4. During MAM over both sub-regions 3 and 4, aerosol effects repress the mean rainfall change between NAT and ACT (i.e., ACT rainfall is lower than NAT). On the other hand, during JJAS over both sub-regions 3 and 4, with lesser aerosol masking effects, ACT has higher mean rainfall than NAT and GHG-only would have noticeably much higher mean rainfall.

Figure 6. Return time plots for MAM daily rainfall ~~during pre-monsoon (MAM) season in~~ under different forcing scenarios over the sub-regions ~~of~~ 1 and 2 of Bangladesh. The ~~HadRM3P~~ ACT (black), ACT highest (~~upper grey with upward triangles~~ sky-blue), ACT lowest (~~lower grey with downward triangles~~ grey), NAT (green) and GHG-only (orange) ensembles are compared with the HAPPI 1.5 (blue) and HAPPI 2.0 (red) ensembles. ~~Anthropogenic warming effects have not strongly influenced the present-day risks of extreme pre-monsoon rainfall in the sub-region1. With a 1.5 or 2.0 degrees' world, this sub-region might see extreme rainfall events with four-fold higher risks.~~ Anthropogenic warming effects have not strongly influenced the present-day risks of extreme MAM rainfall over sub-region 1 (Fig. 6a). With a 1.5 or 2.0 degrees' world, this sub-region might see extreme rainfall events with four-fold higher risks.

Figure 7. Same as Fig 6, but showing return time plots for MAM daily rainfall ~~during pre-monsoon (MAM) season in~~ under different forcing scenarios over the sub-regions ~~of~~ 3 and 4 of Bangladesh.

Figure 8. Return time plots for daily rainfall during monsoon (JJAS) season in different forcing scenarios over the sub-regions of 1 and 2 of Bangladesh. The HadRM3P ACT (black), ACT highest (upper grey with upward triangles), ACT lowest (lower grey with downward triangles), NAT (green) and ~~GHG~~ GHG-only (orange) ensembles are compared with the HAPPI 1.5 (blue) and 2.0 (red)

ensembles. The most significant changes in the risks of extreme monsoon rainfall take place in the sub-region2, which is already the wettest part of Bangladesh.

Figure 9. Same as Fig 8, but showing return time plots for daily rainfall during monsoon (JJAS) season in different forcing scenarios over the sub-regions of 3 and 4 of Bangladesh.

Figure 10. The risk ratios of four specific rainfall events with return periods of 10, 20, 50, and 100 years between ~~Actual/Natural~~ ACT/NAT, HAPPI 1.5/NAT ~~Natural~~, HAPPI 2.0/NAT ~~Natural~~ and ~~GHG~~ GHG-only /ACT ~~Actual~~ over the two northern sub-regions ~~of~~ 1 and 2 during ~~of Bangladesh in pre-monsoon (~~MAM~~)~~ (~~shown in~~ top two panels of a. ~~and~~ & b.) and ~~monsoon (~~JJAS~~)~~ (~~shown in~~ bottom two panels of c. ~~and~~ & d.) ~~seasons~~. The error bars indicate the associated uncertainty range with 95% confidence level for individual event. ~~This figure demonstrates that the uncertainty range increases with the increase of the return periods of rainfall events (i.e., rarer events) in most of the cases, which should be considered in the risk assessment process. While there is no discernible climate change impacts on the current risks (i.e., all four risk ratios are ~1), in a1.5°C world there would be 4 (with uncertainty range 2.0-7.0) times increase in the risks of extreme rainfall events of 100 years return period over sub-region 1 during pre-monsoon season (top-left panel a.).~~

Figure 11. ~~The risk ratios of four specific rainfall events with return periods of 10, 20, 50, and100 years between Actual/Natural, HAPPI 1.5/Natural, HAPPI 2.0/Natural and GHG/Actual over the two southern sub-regions of 3 and 4 of Bangladesh in pre-monsoon (MAM) (shown in top two panels of a. and b.) and monsoon (JJAS) (shown in bottom two panels of c. and d.) seasons. The error bars indicate the associated uncertainty range with 95% confidence level for individual event.~~ Same as Fig 10, but for MAM and JJAS risk ratios over the two southern sub-regions 3 and 4. ~~The risk ratios over sub-region 4 in monsoon (bottom right panel d.) indicate that the extreme rainfall events with 100 years return period are already made 3.9 (with uncertainty range 2.6-5.8) times likely in the actual climate compared to the events of natural climate. With additional global warming effects the same event will become 4.1 (with uncertainty range 2.2-5.3) and 5.5 (with uncertainty range 3.5-7.8) times likely in a 1.5 and 2.0 degrees' worlds.~~

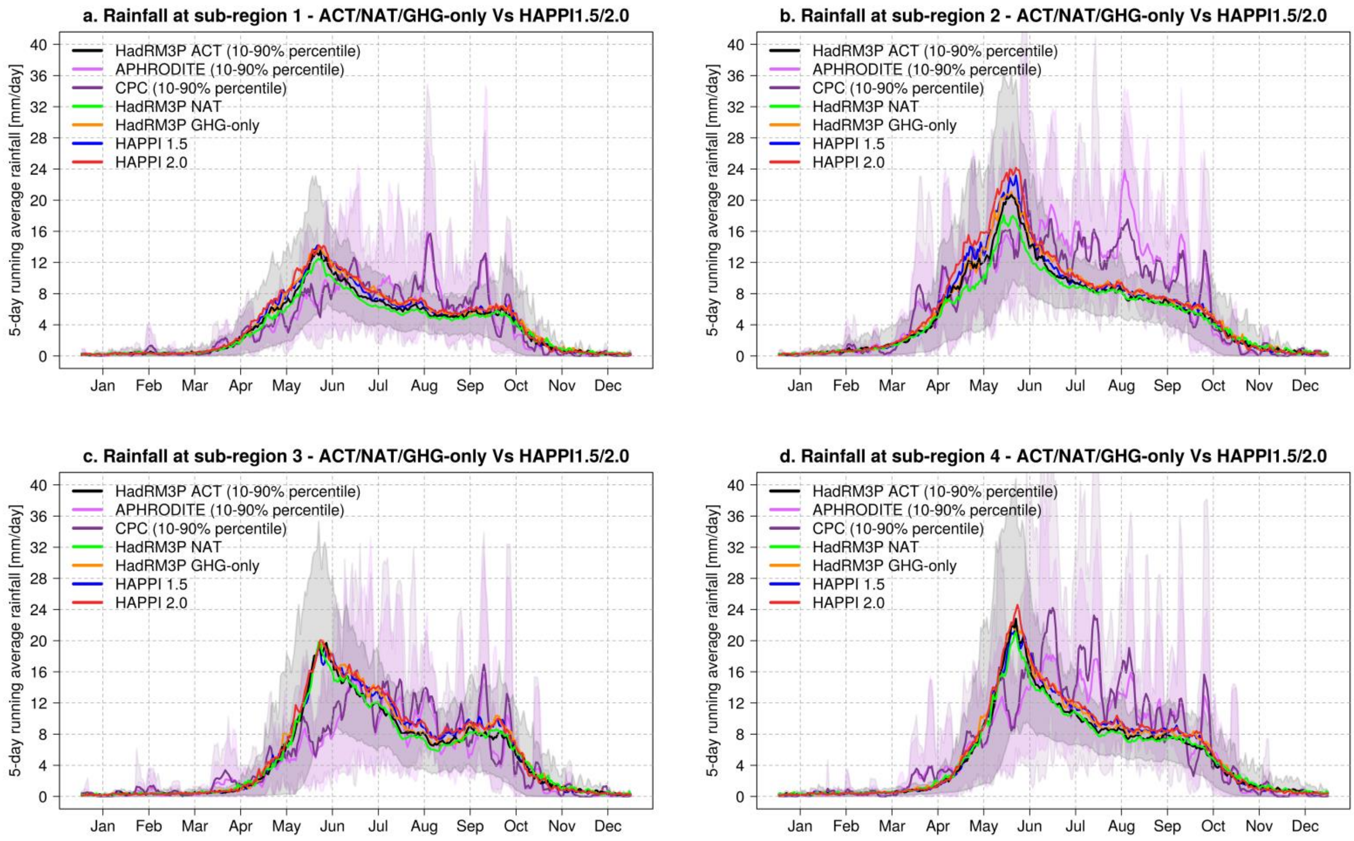

Figure 1. Seasonal cycles of five day mean rainfall under different forcing scenarios over the four sub-regions of Bangladesh. The ACT (black), NAT (green) and GHG-only (orange), HAPPI 1.5 (blue) and 2.0 (red) ensembles are compared with the observations from APHRODITE (dark purple) and CPC (dark purple). The model adequately captures the seasonal cycle of rainfall compared to observation but underestimates monsoon rainfall. Only over sub-region 2, rainfall is clearly shifting from NAT to ACT, from ACT to GHG-only, from ACT to HAPPI 1.5 and from HAPPI 1.5 to 2.0 forcing scenarios.

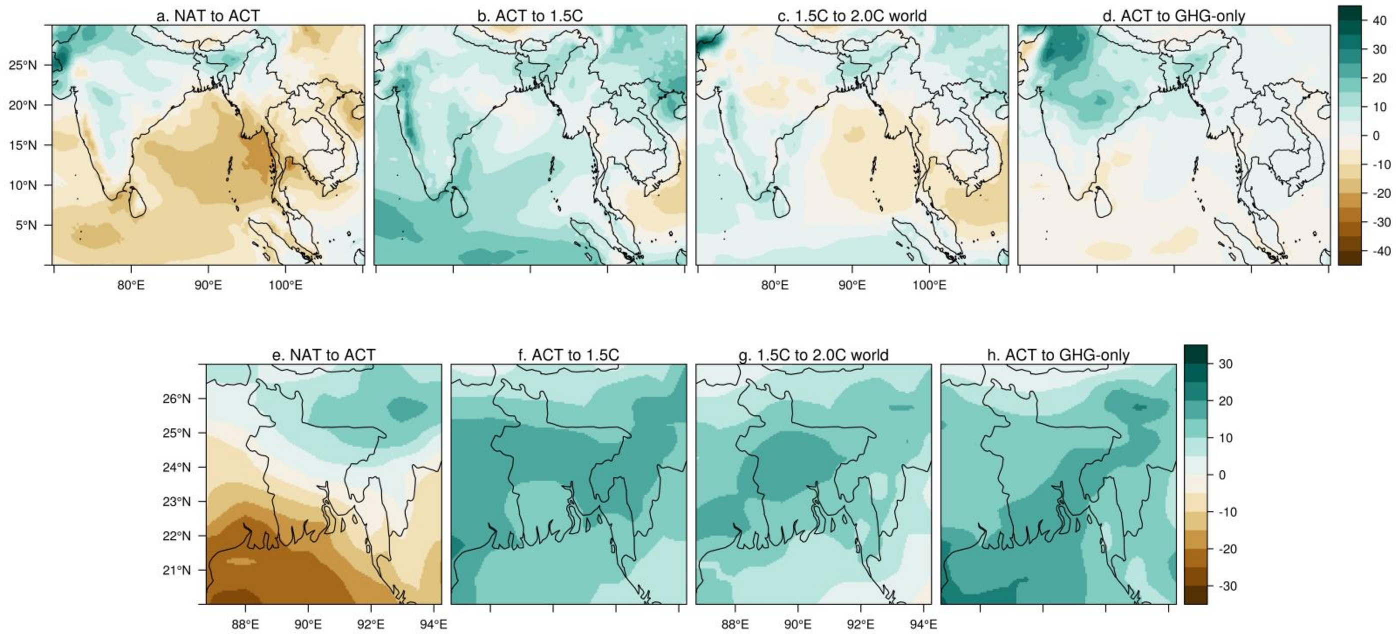

Figure 2. Percentage change (PC) in MAM mean rainfall between different forcing scenarios. The top row (panels a-d) shows the regional PC over central parts of the South Asia. a. ACT rainfall PC relative to NAT over SA b. ACT rainfall PC relative to HAPPI 1.5°C over SA c. HAPPI 1.5°C rainfall PC relative to HAPPI 2.0°C over SA d. ACT rainfall PC relative to GHG-only. Bottom row (panels e-h) shows PC in the same way but over Bangladesh. The four boxes (1-4) on top of the panel e represent the four sub-regions of Bangladesh.

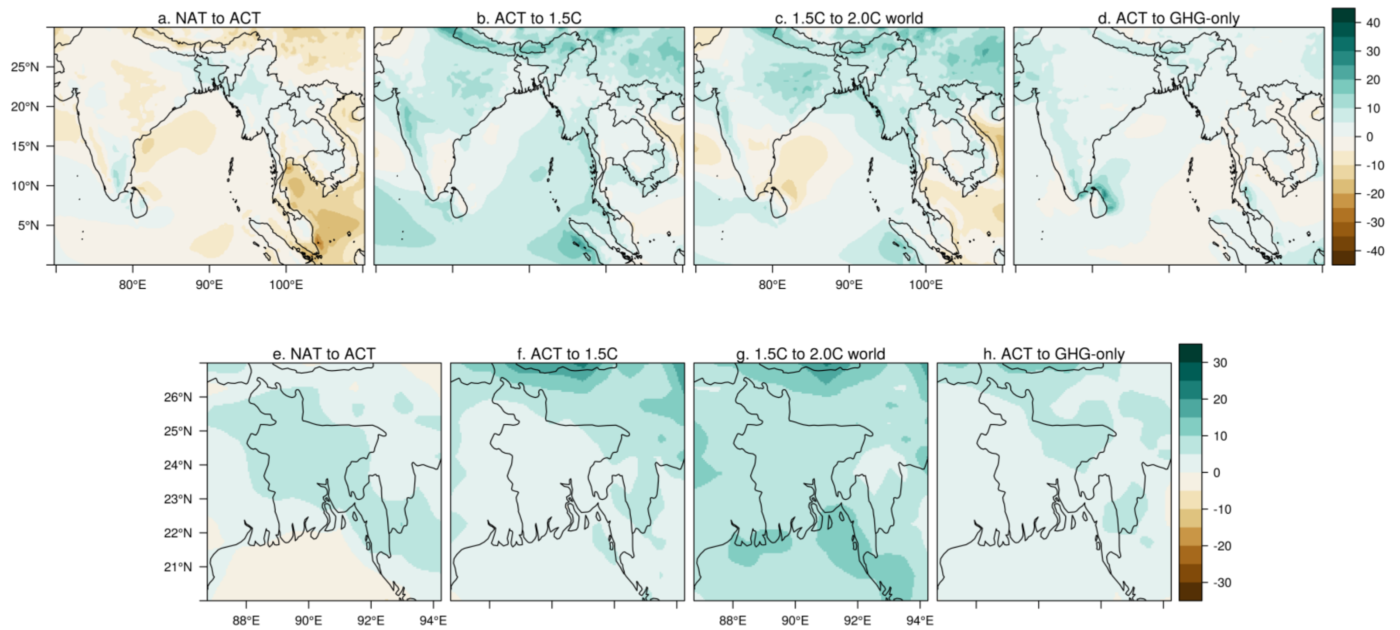

Figure 3. Same as Fig. 2, but for JJAS rainfall PC. This figure shows that the apparently non-linear response between panels of a, b, and c (or, e, f, g) can be explained by the response for GHG-only (anthropogenic aerosols reduced to pre-industrial levels) in the panel d (or, h).

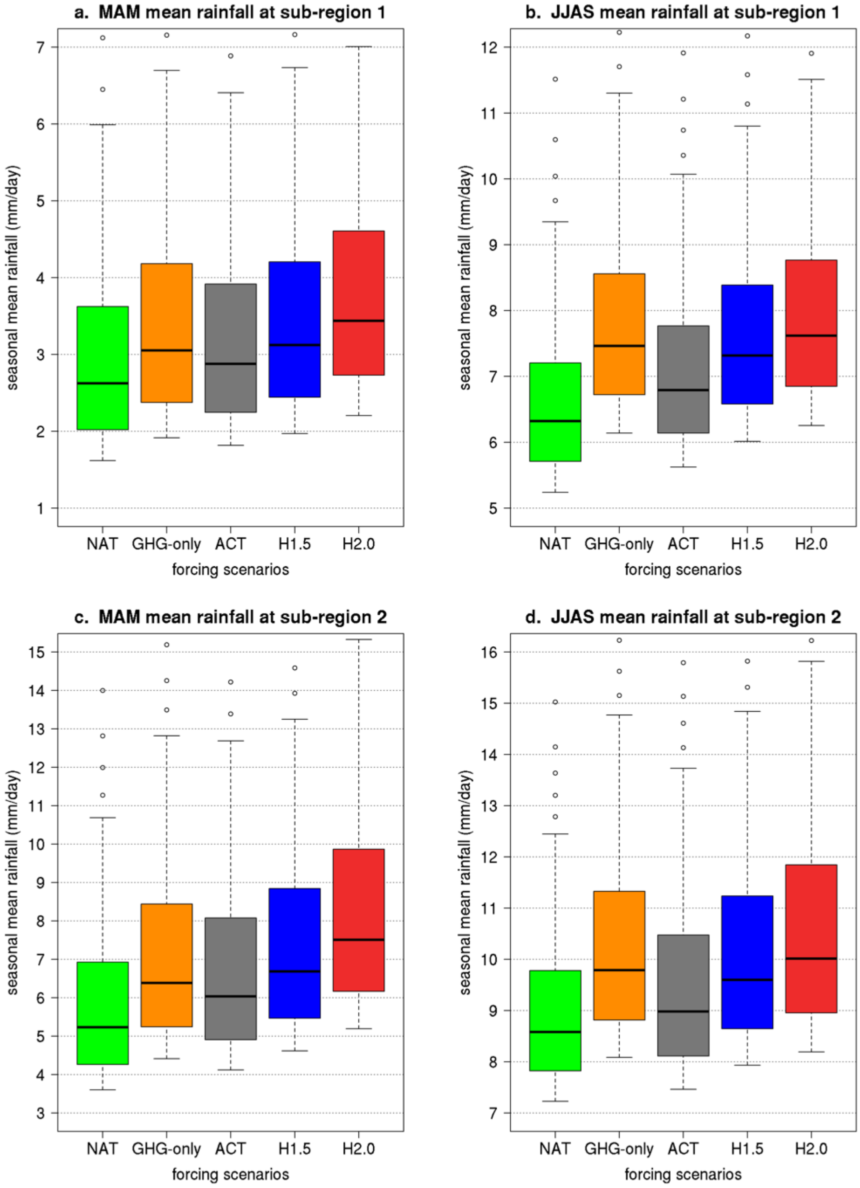

Figure 4. Seasonal mean rainfall in MAM (left column) and JJAS (right column) over the sub-regions 1 and 2 (top and bottom row) of Bangladesh. Green, orange, grey, blue and red colours represent NAT, GHG-only, ACT, HAPPI 1.5 and HAPPI 2.0 ensembles respectively. Each panel has different y-scale range to clearly indicate the details of changes in the median values between different model ensembles. The horizontal black line in each box indicates the median value, the bottom and top limits of the box represents the 25th and 75th percentiles respectively. The figure shows that aerosol impacts over both sub-regions 1 and 2 are larger in MAM dry season than that in JJAS wet season.

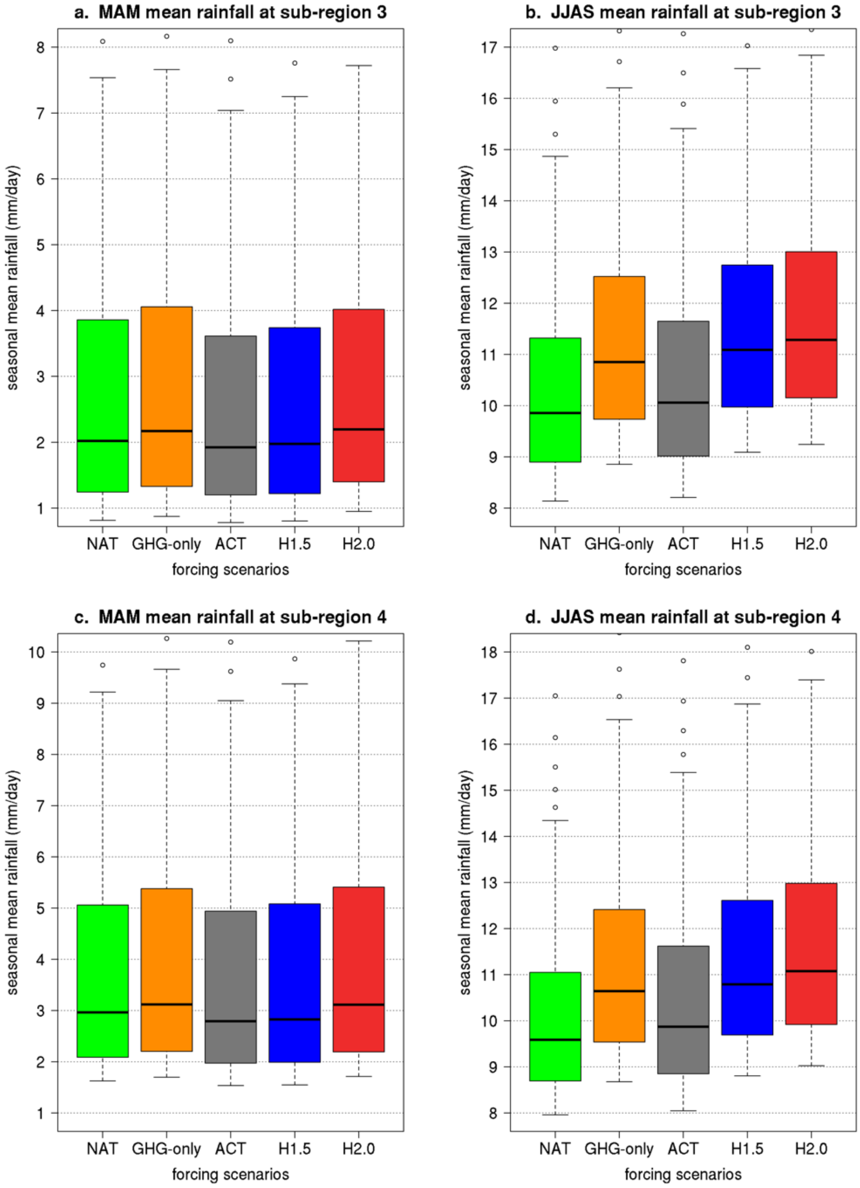

Figure 5. Same as Fig. 4, but for sub-regions 3 and 4. During MAM over both sub-regions 3 and 4, aerosol effects repress the mean rainfall change between NAT and ACT (i.e., ACT rainfall is lower than NAT). On the other hand, during JJAS over both sub-regions 3 and 4, with lesser aerosol masking effects, ACT has higher mean rainfall than NAT and GHG-only would have noticeably much higher mean rainfall.

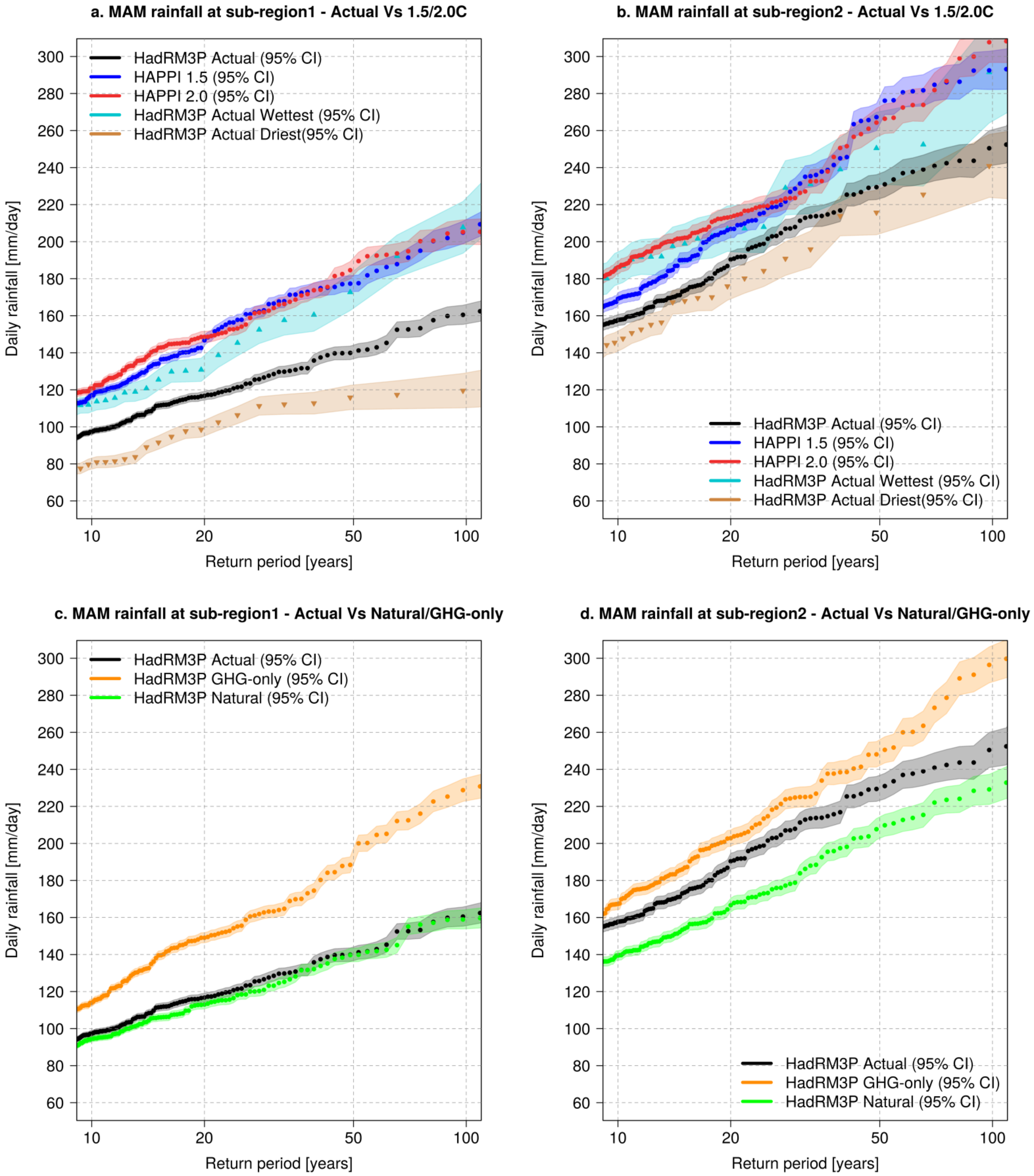

Figure 6. Return time plots for MAM daily rainfall under different forcing scenarios over the sub-regions 1 and 2 of Bangladesh. The ACT (black), ACT highest (sky-blue), ACT lowest (grey), NAT (green) and GHG-only (orange) ensembles are compared with the HAPPI 1.5 (blue) and HAPPI 2.0 (red) ensembles. Anthropogenic warming effects have not strongly influenced the present-day risks of extreme MAM rainfall over sub-region 1 (Fig. 6a). With a 1.5 or 2.0 degrees' world, this sub-region might see extreme rainfall events with four-fold higher risks.

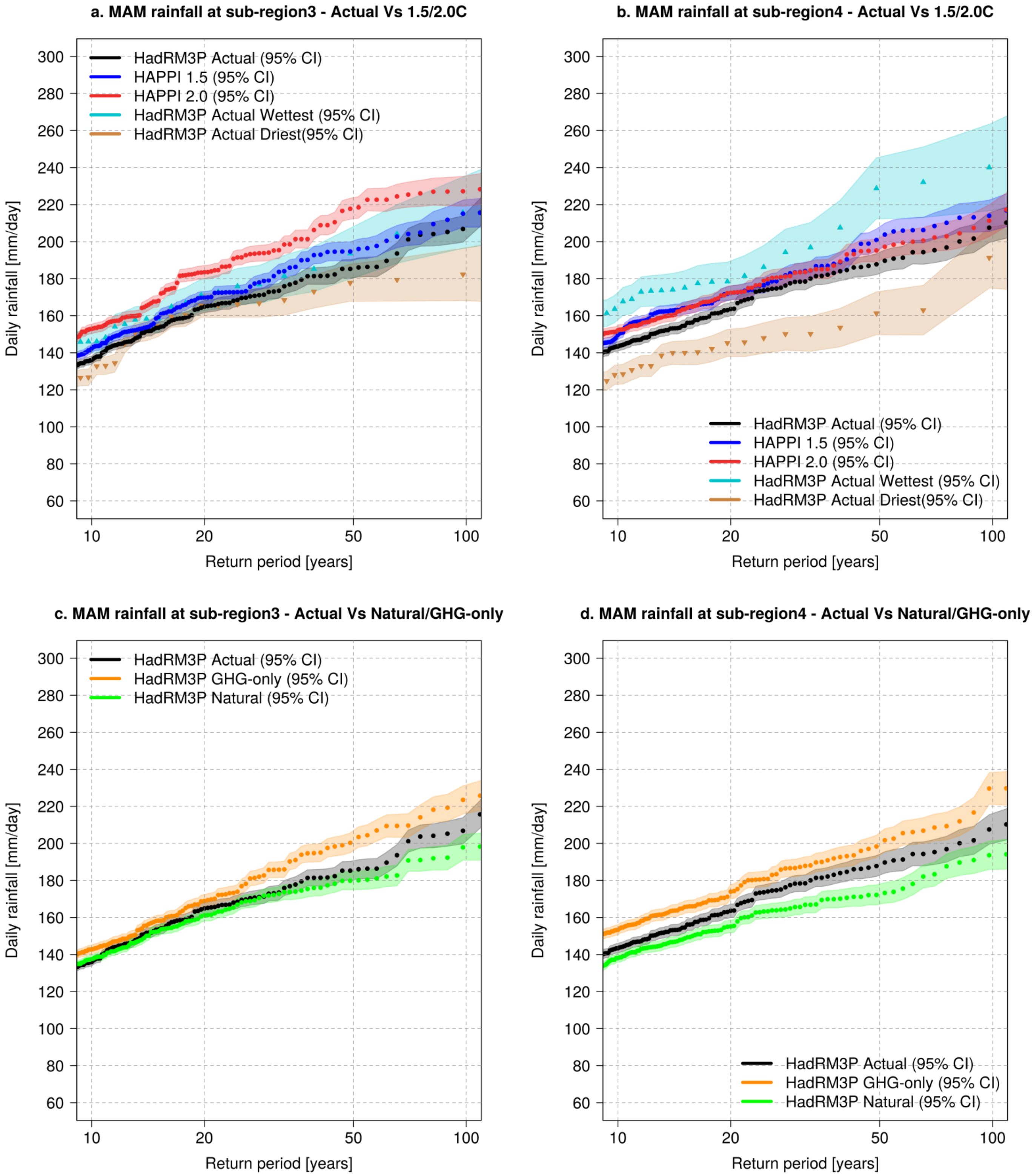

Figure 7. Same as Fig 6, but showing return time plots for MAM daily rainfall under different forcing scenarios over the sub-regions 3 and 4 of Bangladesh.

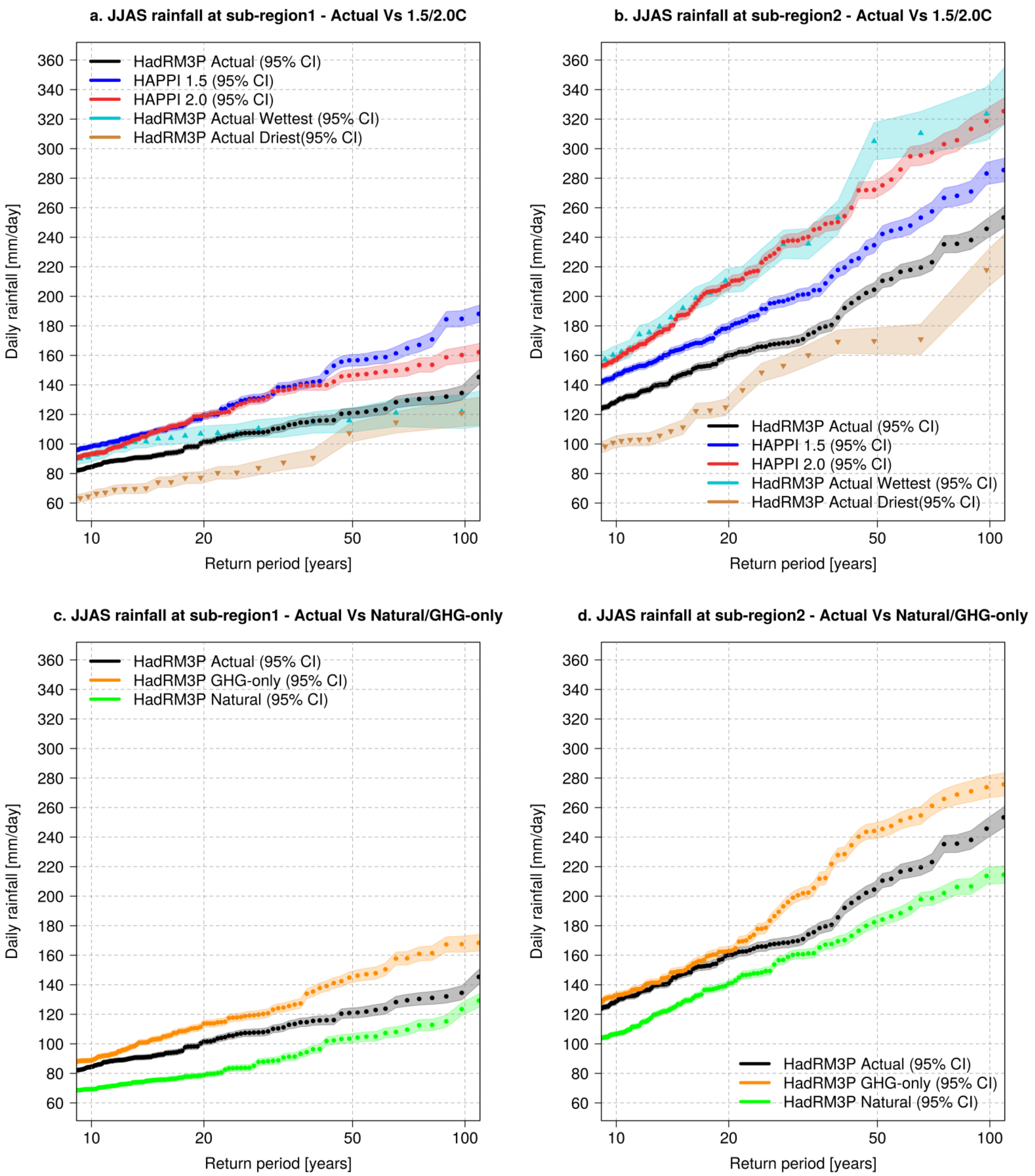

Figure 8. Return time plots for daily rainfall during monsoon (JJAS) season in different forcing scenarios over the sub-regions of 1 and 2 of Bangladesh. The HadRM3P ACT (black), ACT highest (upper grey with upward triangles), ACT lowest (lower grey with downward triangles), NAT (green) and GHG-only (orange) ensembles are compared with the HAPPI 1.5 (blue) and 2.0 (red) ensembles. The most significant changes in the risks of extreme monsoon rainfall take place in the sub-region2, which is already the wettest part of Bangladesh.

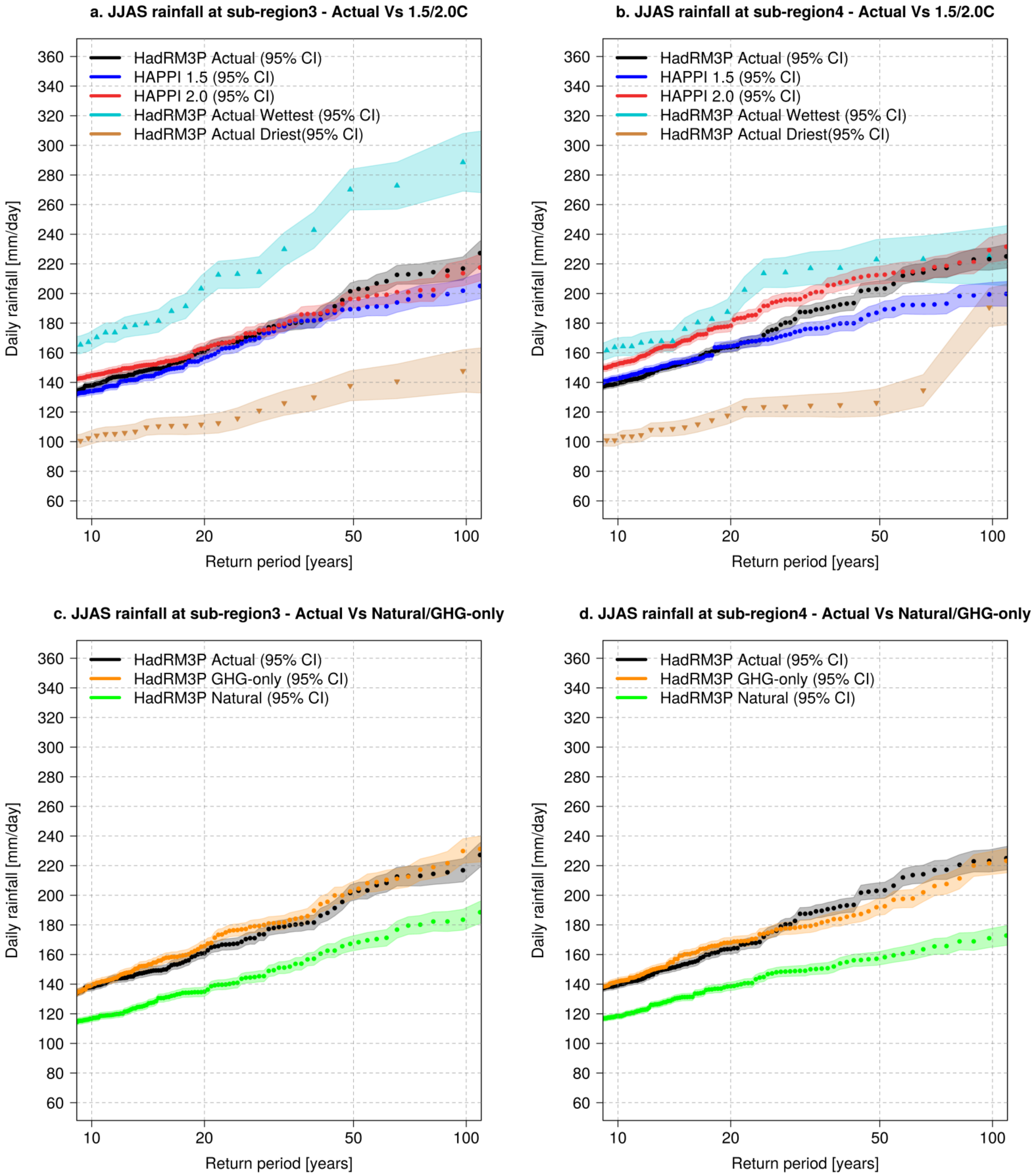

Figure 9. Same as Fig 8, but showing return time plots for daily rainfall during monsoon (JJAS) season in different forcing scenarios over the sub-regions of 3 and 4 of Bangladesh.

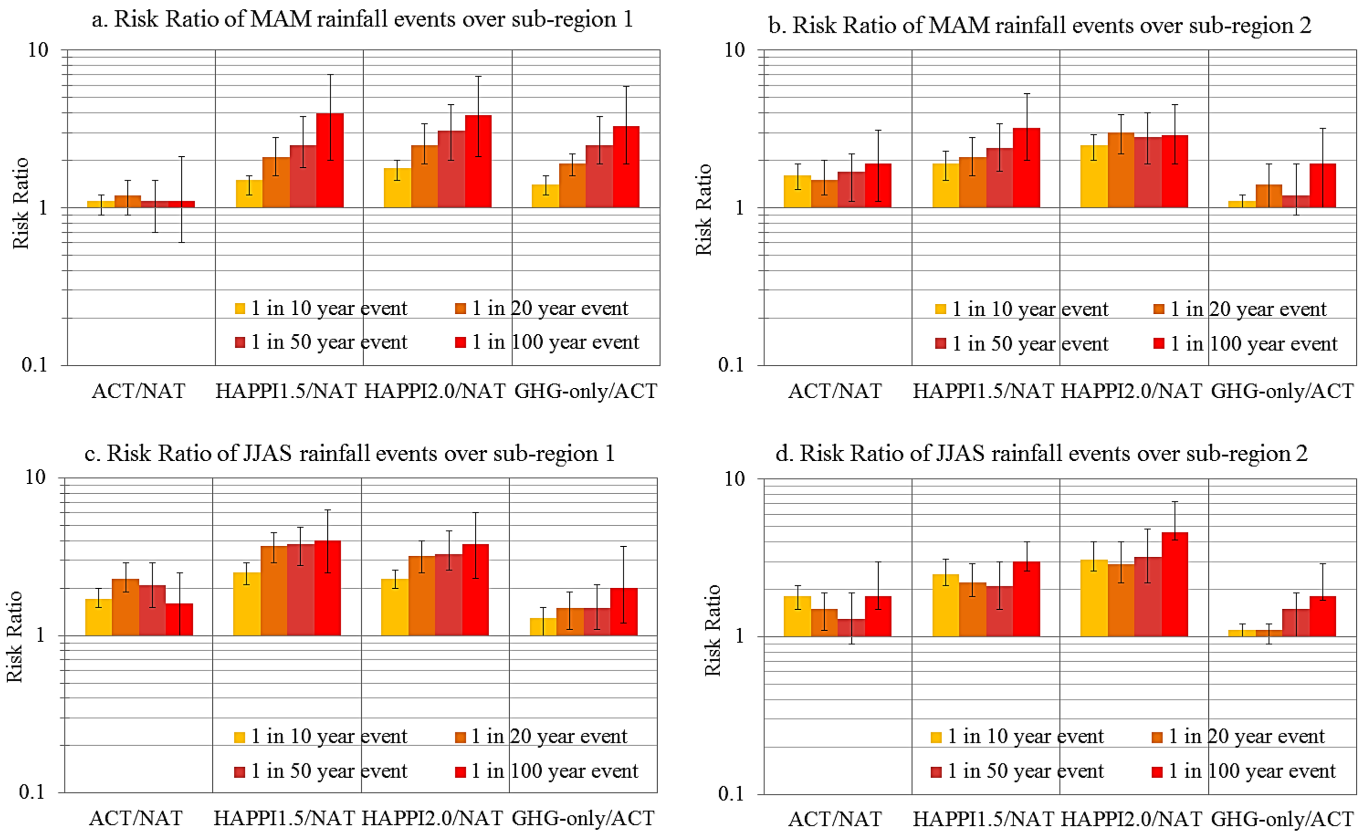

Figure 10. The risk ratios of four specific rainfall events with return periods of 10, 20, 50, and 100 years between ACT/NAT, HAPPI 1.5/NAT, HAPPI 2.0/NAT and GHG-only /ACT over the two northern sub-regions 1 and 2 during MAM (top two panels of a. & b.) and JJAS (bottom two panels of c. & d.). The error bars indicate the associated uncertainty range with 95% confidence level for individual event.

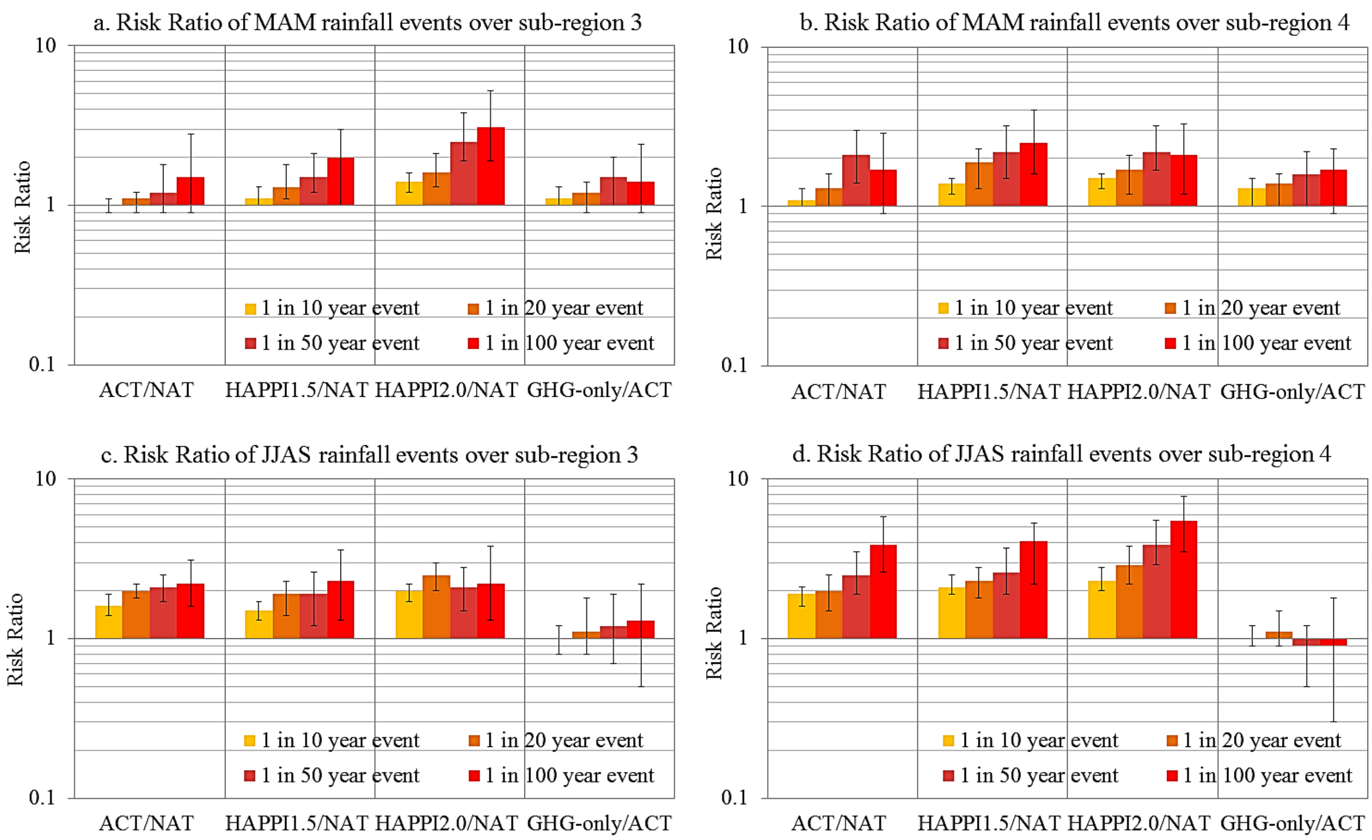

Figure 11. Same as Fig 10, but for MAM and JJAS risk ratios over the two southern sub-regions 3 and 4.

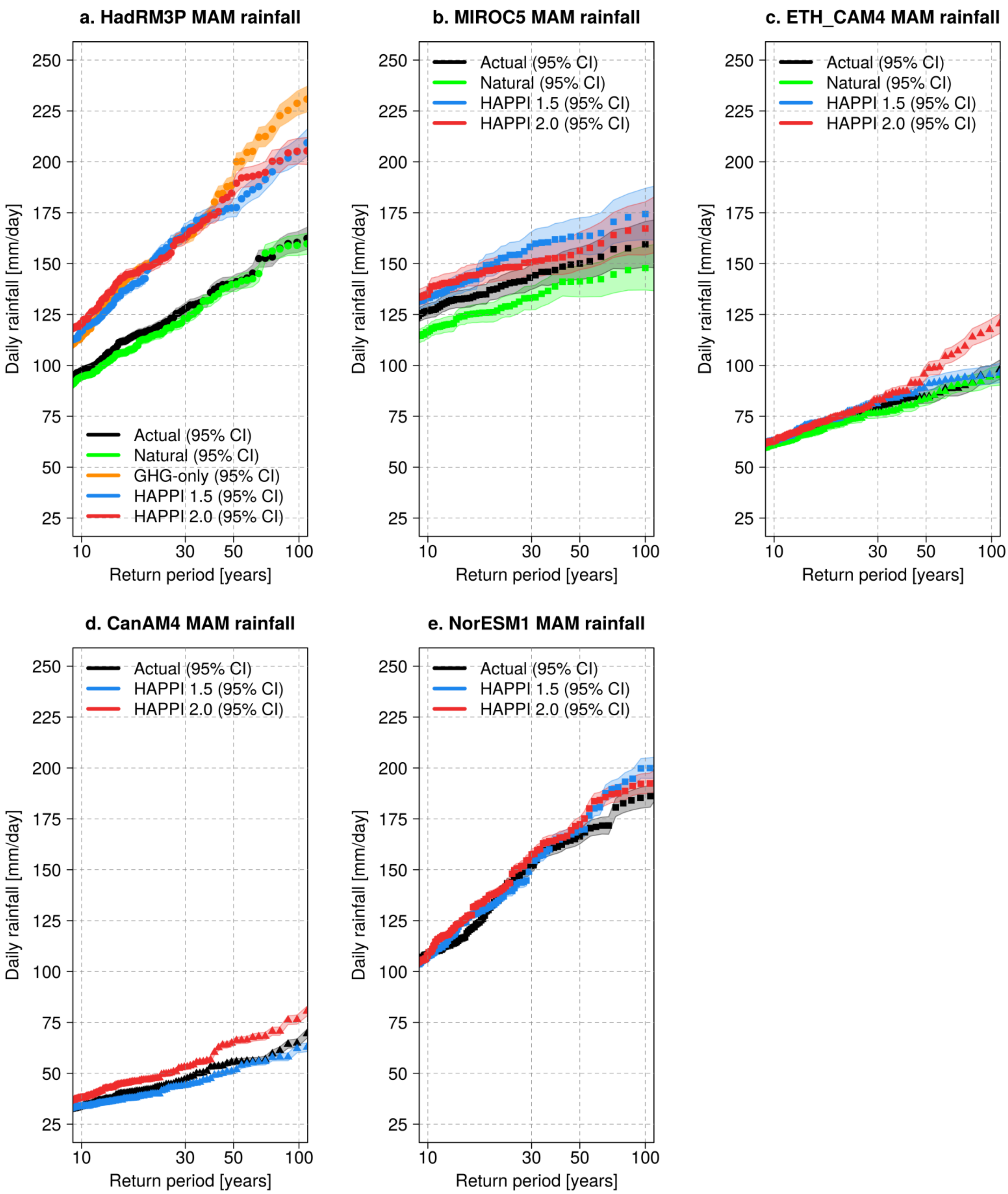

Figure 12. Comparative return periods (10-100 year events) of MAM daily rainfall (mm/day) over sub-region 1 during 1986-2015 as per (a) HadRM3P, (b) MIROC5, (c) ETH_CAM4, (d) CanAM4 and (e) NorESM1 models. ACT, NAT, GHG-only, plus 1.5°C and 2.0°C model ensembles are shown in black, green, orange, blue and red colours respectively..

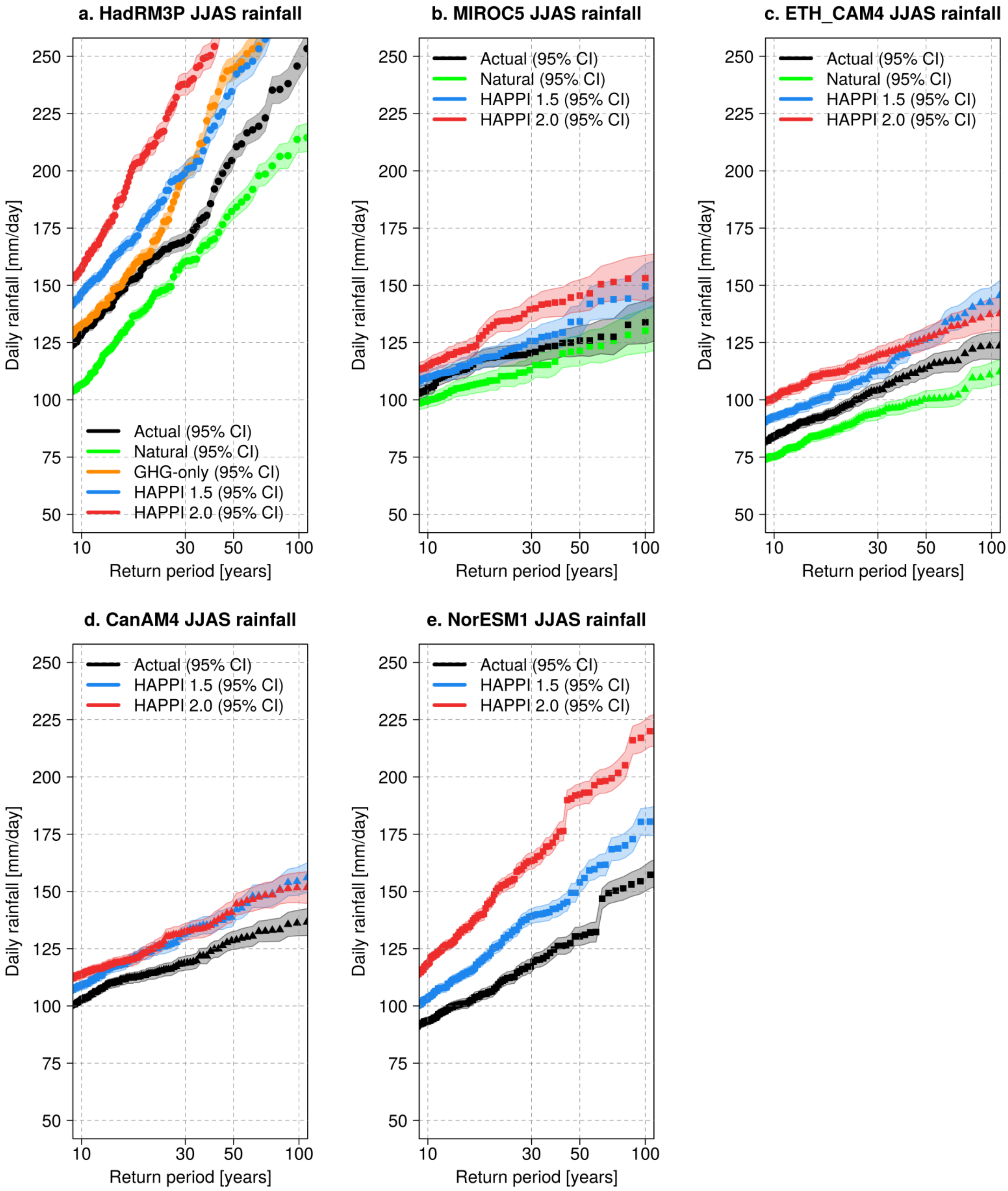

Figure 13. Comparative return periods (10-100 year events) of JJAS daily rainfall (mm/day) over sub-region 2 during 1986-2015 as per (a) HadRM3P, (b) MIROC5, (c) ETH_CAM4, (d) CanAM4 and (e) NorESM1 models. ACT, NAT, GHG-only, plus 1.5°C and 2.0°C model ensembles are shown in black, green, orange, blue and red colours respectively.

5